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THE UNIVERSITY OF ALBERTA

# PILOT PLANT INVESTIGATION OF THE BIOLOGICAL PHOSPHORUS REMOVAL PROCESS

by

EDWARD DOYLE

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE
IN
ENVIRONMENTAL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA

FALL 1987

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Daniel W. Smith

Supervisor

P. Fedorak

Date 30 Sept 87

# ABSTRACT

The phenomenon of phosphorus uptake by microorganisms in excess of normal metabolic requirements is currently receiving worldwide application in municipal wastewater treatment. Previous studies have identified several conditions necessary for the successful operation of biological phosphorus removal plants. The objective of this research was to evaluate the process as applied to Edmonton, Alberta municipal wastewater and to quantify the effects on the process of three controllable factors. Aerobic nominal detention time, anaerobic nominal detention time and sludge age were chosen for investigation.

A full $2^3$ factorial design experiment was used to best quantify factor effects and interactions over a ten day intensive testing period. Statistical testing was applied to ensure validity in the obtained results. Varying degrees of biological phosphorus removal were achieved in each of eight bench scale activated sludge units used in the study.

The setting of anaerobic detention time for successful biological phosphorus removal depended strongly on the simultaneous setting of aerobic detention time and vice versa. The aerobic detention time x anaerobic detention time interaction was significant at the 95% or greater level over 80% of the sampling period. The sludge age setting was found to be significant at the 90% level.

The optimum setting, over the range studied, for biological phosphorus removal was a high level combination

of each of the three factors. The results showed that these settings might be expected to decrease COD removal efficiency slightly.

A strong correlation between influent wastewater characteristics and phosphorus removal efficiency could not be established, though influent COD versus effluent phosphorus was considered worthy of further research. Phosphorus removal efficiency decreased regularly in all reactors on a post-weekend basis. This was considered a result of, as yet, unidentified influent wastewater characteristics.

Profile analysis through the reactors showed that oxidation-reduction potential appeared to be inversely related to phosphorus concentration. However, lack of reproducibility precluded its use as a tool to predict phosphorus removal.

A simple linear predictive model incorporating only the three factors investigated failed to adequately describe the process.

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## LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| ADP | Adenosine Diphosphate |
| AMP | Adenosine Monophosphate |
| ATP | Adenosine Triphosphate |
| $b_{hT}$ | Endogenous mass loss rate for heterotropic organisms at T° C ($d^{-1}$) |
| bioP | Biological Phosphorus |
| BOD | Biochemical Oxygen Demand, mg/L |
| $BOD_5$ | Five day BOD |
| $BOD_f$ | Filtered BOD |
| BODS | Soluble BOD |
| $BOD_{uf}$ | Unfiltered BOD |
| COD | Chemical Oxygen Demand, mg/L |
| $COD_f$ | Filtered COD |
| $COD_{uf}$ | Unfiltered COD |
| DNA | Deoxyribonucleic Acid |
| EM | Embden-Meyerhof Metabolic Pathway |
| f | Unbiodegradable fraction of active mass |
| $f_p$ | Phosphorus fraction of the inert mixed liquor suspended solids |
| $f_{up}$ | Particulate unbiodegradable COD fraction of the influent COD |
| $f_{us}$ | Soluble unbiodegradable COD fraction of the influent COD |
| $f_{xa}$ | Anaerobic sludge mass fraction |
| F/M | Food to microorganism ratio |

| | |
|---|---|
| $F_s/M$ | Soluble food to microorganism ratio |
| $h_1$ | Proportionality constant, mg/L |
| $h_2$ | Proportionality constant |
| $K_1$, $K_2$ | Rate constants, 1/mg/hr |
| $K_s$ | Saturation constant |
| MCRT | Mean Cell Residence Time, days |
| mg/L | Milligrams per litre |
| mM/L | Millimoles per litre |
| n | Fraction of total mass of sludge in process passing through the anaerobic reactor per day |
| NAD | Nicotinamide Adenine Dinucleotide |
| $NADH_2$ | Reduced Nicotinamide Adenine Dinucleotide |
| $NO_2$-N | Nitrite Nitrogen |
| $NO_3$-N | Nitrate Nitrogen |
| ORP | Oxidation-reduction potential, mV |
| PE | Primary Effluent |
| $P_i$ | General orthophosphate form |
| $(P_i)_n$ | General polyphosphate form |
| $P^*$ | Maximum possible internal storage of polyphosphate by bacteria, mg/L |
| PS | Soluble phosphate, mg/L |
| PI | Polyphosphate stored internally by the biomass, mg/L |
| $P_f$ | Excess phosphorus removal propensity factor |

| | |
|---|---|
| $P_v$ | COD/Volatile suspended solids ratio of the volatile sludge mass |
| PEP | Phospheonolpyruvic Acid |
| $PO_4$-P | Phosphate phosphorus |
| PHB | Poly-$\beta$-hydroxybutyrate |
| $R_{an}$ | Actual anaerobic retention time, hr |
| $R_{BOD}$ | Rate of biological absorption of BOD, mg/L/hr |
| $R_S$ | Sludge Age |
| RNA | Ribonucleic Acid |
| $S_{ba}$ | Concentration of rapidly biodegradable COD in the anaerobic reactor, mg/L |
| SBR | Sequencing Batch Reactor |
| SRT | Solids Retention Time, days |
| TCA | Tricarboxylic Acid, or Krebs, Metabolic Cycle |
| TKN | Total Kjeldahl Nitrogen |
| TNFR | Total Non-Filterable Residue |
| TP | Total Phosphorus |
| VFA | Volatile Fatty Acid |
| VNFR | Volatile Non-Filterable Residue |
| X | Active biomass mg/L |
| $\mu_{max}$ | max specific growth rate, hr$^{-1}$ |
| $\Delta P_s$ | Increment of process phosphorus removed in daily sludge wastage, mgP/L of influent |
| $\gamma$ | Coefficient of excess phosphorus removal |
| 2,4-DNP | 2,4-dinitrophenol |

# 1. INTRODUCTION

The problems associated with the high phosphorus content of many municipal wastewater treatment plant effluents have been recognized for some time. The major concern has been the eutrophication caused in receiving waters by phosphorus, as the growth-limiting plant nutrient. Eutrophication causes problems ranging from flow retardation, especially in smaller rivers and streams, to algal blooming and consequent taste and odour problems in drinking waters. The increase in associated biological activity can also cause rapid depletion of dissolved oxygen in receiving waters thus posing a threat to aquatic life.

Due to the ability of some forms of microbial life, notably cyanobacteria (blue-green algae), to fix gaseous atmospheric nitrogen and use it as a nutrient, it is often more advantageous to limit the availability of phosphorus. Until the early nineteen-seventies the only practical removal method was that of chemical precipitation and removal of phosphorus, using metal salts such as aluminum sulphate and ferric chloride. While this is a reliable method which gives good removal the cumulative chemical cost is often prohibitive. In addition the extra sludge, which tends to be difficult to dewater, causes further treatment expense.

Therefore demonstration both in the United States and South Africa of consistent phosphorus removal in modified activated sludge processes, without chemical addition, aroused worldwide interest. Continued research resulted in the identification of the major factors and conditions necessary to bring about phosphorus removal by biological means. These included the formation of an anaerobic zone prior to the normal aerated reaction zone. This anaerobic zone served as a conditioning stage which was necessary for the phosphorus removing microorganisms.

Other variables affecting the process were:

1. the cultivation of a large fraction of phosphorus removing microbes within the microbial population;
2. the availability of a rapidly biodegradable organic substrate within the anaerobic zone;
3. the complete absence of nitrates in the return sludge; and
4. sufficient detention time in the anaerobic zone to allow for conditioning and in the aerobic zone to allow for phosphorus uptake.

On the basis of these findings, biological phosphorus removal is now achieving the status of a reliable and controllable method of phosphorus removal from wastewater.

In order to evaluate the suitability of biological phosphorus removal for full-scale implementation in Edmonton, Alberta, the City of Edmonton Water and Sanitation Department and Alberta Environment implemented a two-part process evaluation.

Part one, initiated in April 1985, involved the modification of part of the process train in Edmonton's Gold

Bar wastewater treatment plant to enhance the growth of a phosphorus-removing microbial population and to operate under conditions favouring biological phosphorus removal. The plant and intended operating conditions for this full-scale study have been described elsewhere (Shivji, 1983) and will not be discussed further here.

The second part of the investigation involved a small-scale on-site pilot plant study. Prior to the initiation of the pilot plant operation an extensive literature review was carried out in order to identify the major contributing factors to the process. This literature review forms Chapter 2 of this thesis. Special attention was given to ascertaining which of these parameters were operator controllable and to the useful range of operation. It was decided that the application of a full $2^3$ factorial design experiment would most efficiently and completely determine the effects and interactions of three controllable parameters. To this end, ten small scale models consisting of anaerobic reactors, aerobic reactors, clarifiers and return sludge pumping were constructed and put into operation during the summer of 1985. The design and construction of the pilot plant are described in greater detail in Appendix I.

The objectives of the pilot plant study were:

1. to model a large scale phosphorus removing treatment plant;
2. to achieve biological phosphorus removal using municipal

wastewater;

3. to investigate the effects of three important controllable variables on the process and to determine the level of interaction, if any, between these variables.

It was believed that the information gained from the pilot plant study would help to move the full scale process into its optimum operability range.

# 2. REVIEW OF THE LITERATURE

## 2.1 OVERVIEW OF BIOLOGICAL PHOSPHORUS REMOVAL

Biological phosphorus removal in an activated sludge wastewater treatment plant involves the uptake and storage of phosphorus by microorganisms, chiefly bacteria. The quantity of phosphorus taken up is greater than that previously considered necessary for the immediate biochemical requirements of the microorganisms.

Biological phosphorus removal plants consist firstly of an anaerobic zone or cycle in which previously stored phosphorus is released by the bacteria to the surrounding medium. The anaerobic zone or cycle is followed by an aerobic zone or cycle in which the phosphorus is reincorporated into the bacterial cells. The extra phosphorus, from the influent wastewater, is taken up by the additional bacteria, which have resulted from reproduction. The phosphorus is removed from the process train within the waste activated sludge, in a totally biological system or through chemical precipitation of released phosphorus in the anaerobic zone of a combined chemical-biological system.

## 2.2 THE ANAEROBIC ZONE IN BIO-P REMOVAL PLANTS.

Levin and Shapiro (1965) reported on experimental work carried out in order to investigate the nature of biological phosphorus removal, as originally reported by Srinath *et al.* (1959) and Alarcon (1961). They found that leakage of orthophosphate from activated sludge suspended solids occurred when the mixed liquor was not aerated. They also found that subsequent to phosphorus release or stripping (in this case by exposure to an acidic environment) the bacteria had an increased ability to take up phosphorus. Phosphorus release under anaerobic conditions was also shown by Sekikawa *et al.* (1966). Shapiro (1967) noted that greater than 40% of stored phosphorus was released by the suspended solids in three and a half hours of anaerobic conditions. Thus early in biological phosphorus removal research the phenomenon of phosphorus release under anaerobic conditions was established. It was at this time, however, seen as a step to be avoided rather than encouraged.

The reversibility of the phosphorus release within the anaerobic zone was also shown by Shapiro (1967) when he reaerated some anaerobic sludge and achieved a reincorporation of the phosphorus. In the late nineteen sixties and early nineteen seventies various authors reported phosphorus removal, by biological means, in excess of 70% in several full-scale plants in the United States (Vacker *et al.*, 1967; Scalf *et al.*, 1969; Bargman *et al.*, 1970; Witherow and Kerr, 1969) These plants were all conventional plug-flow activated sludge plants. Vacker *et al.* (1967) noted low dissolved oxygen levels in the influent end of the Rilling Plant in San Antonio, Texas. This was due in part to clogging of the air diffusion tubes in the front end of the aeration reactor. The dissolved oxygen in the effluent end of the reactor was often between 4 and 6 mg/L. This was greater than the effluent end dissolved oxygen concentration in the other two similar plants in San Antonio which did not achieve the same level of success in phosphorus removal. Sampling through the aeration reactor showed a soluble orthophosphate concentration of 43 to 68 mg/L at the influent end of each of the four treatment trains. This concentration fell gradually along the reactor length to a concentration of less than 1 mg/L in all four cases.

Scalf *et al.* (1969) described work carried out at the Black River Sewage Works of Baltimore, Maryland. They showed that in both of two aeration tanks, dissolved oxygen concentration was low in the influent end and dissolved orthophosphate concentration was high. At the effluent end the situation was reversed with a high dissolved oxygen concentration and a low orthophosphate concentration. A heavy slime growth on the diffusion plates in aeration tank number two was blamed for the low dissolved oxygen concentration in this tank.

In a plug flow type aeration tank, the sludge at the influent end is subjected to the heaviest loading of carbonaceous substrate and consequently the highest oxygen demand. Therefore the dissolved oxygen in the influent end will be depleted more rapidly than anywhere else in the plug flow reactor. This coupled with poor aeration capability may have caused zones of anaerobiosis in the influent end of the plants reporting excess phosphorus removal.

At this stage many researchers were aware of phosphorus release under low dissolved oxygen conditions in the influent end of the aeration tanks. They did not however view this as a necessity for biological phosphorus removal and believed that removal depended more on higher than normal aeration rates within the second half of the tank.

Levin and Shaheen (1967) had suggested that stripping of phosphorus from the phosphorus-rich sludge would be necessary since the sludge would otherwise become phosphorus saturated after several cycles through the aeration basin. They also recommended anaerobic storage as preferable to acidification for phosphorus stripping. In 1972, Levin introduced the first commercial biological phosphorus removal system (Levin *et al.*, 1972). This system, termed the PhoStrip Process, is a combined biological-chemical precipitation system which utilizes anaerobic zone release of phosphorus. The first statement to suggest that the provision of an anaerobic zone was vital to the biological phosphorus removal process came from Barnard (1974). In work with a biological nutrient removal plant, termed the Bardenpho Process (Barnard, denitrification, phosphorus removal), he found that nitrates in the inflow to the anaerobic zone caused a deterioration in phosphorus removal. He suggested that the nitrates prevented the development of the required state of anaerobiosis. This finding was supported by subsequent research (Osborn and Nicholls, 1978;

Nicholls and Osborn, 1979; Barnard, 1982; Malnou *et al.*, 1984).

Currently it is believed that the anaerobic zone provides an environmental advantage to the phosphorus removing bacteria in that it selectively promotes their growth over the other aerobic bacteria in the system. The anaerobic zone may be instrumental in the formation of volatile fatty acids (VFA) such as acetic acid which provide an easily biodegradable substrate for the phosphorus removing bacteria (Marais *et al.*, 1983). This will be discussed in more detail in a later section.

## 2.3 THE AEROBIC ZONE IN BIO-P REMOVAL PLANTS.

In the first reported instance of biological phosphorus removal Srinath *et al.* (1959) reported uptake of water soluble phosphorus upon aeration of activated sludge. Phosphorus removal from raw sewage by sludge was shown to increase with increasing aeration rate (Levin and Shapiro,1965). Also, in several of the full-scale instances of phosphorus removal, elevated dissolved oxygen concentrations were reported. Thus it was thought that enhanced biological phosphorus removal was caused by conditions of oxygen tension alone. It is now known that the actual phosphorus uptake process takes place in the aerobic zone. It is believed that the function of the aerobic zone, in relation to biological phosphorus removal, is to provide non-stress conditions for the phosphorus removing bacteria to allow for uptake and reproduction.

## 2.4 MICROBIOLOGY OF BIOLOGICAL PHOSPHORUS REMOVAL.

### 2.4.1 BIOLOGICAL NATURE OF PHOSPHORUS UPTAKE

The initial reaction to reports of biological phosphorus removal, to the extent reported by Srinath *et al.* (1959) and Alarcon (1961) was one of disagreement. The biological nature of the reported removal was dismissed due to the unfavourable ratio of carbon, phosphorus and nitrogen in sludge bacteria to that of raw sewage. Since $BOD_5$:phosphorus ratios quoted as necessary for nutrition range from 40:1 to 100:1 (Lea and Nichols, 1936; Sawyer, 1944) and since normal domestic wastewater phosphorus content is of the order of 8 to 12 mg-P/L this implies a $BOD_5$ requirement of at least 320 to 480 mg/L for complete phosphorus utilization. This is higher than is usually found in domestic wastewater. The objections therefore seemed reasonable.

Many workers then attempted to demonstrate the biological nature of the process (Levin and Shapiro, 1965; Sekikawa *et al.*, 1966; Yall *et al.*, 1970; Fuhs and Chen, 1975; Hascoet *et al.*, 1985). Levin and Shapiro (1965) in an extensive study used 2,4-dinitrophenol (2,4-DNP) in an attempt to prove that the microorganisms in the sludge were responsible for the uptake. They found that the addition of 2 mM/L of 2,4-DNP to a sludge/raw sewage mixture resulted in an uptake of 10% of $PO_4$-P as opposed to an uptake of 87% in an uninhibited control. Therefore this was taken as evidence for biological phosphorus removal.

The addition of other poisons, such as potassium chromate, also prevented phosphorus removal (Sekikawa *et al.*, 1966). Yall *et al.* (1970) used the radioactive isotope $^{32}P$ to show that most of the phosphorus taken up by the sludge was incorporated into that part of the bacterial cell which would contain the nucleic acids (DNA, RNA) and polyphosphates. In a further refinement Hascoet *et al.* (1985), using $^{31}P$ nuclear magnetic resonance to observe phosphorus forms were able to show that trapped phosphates were stored as polyphosphates. As a result of these and other studies, it is now generally accepted that certain bacteria are capable of enhanced uptake of phosphorus beyond normal metabolic requirements.

### 2.4.2 PHOSPHORUS STORAGE WITHIN PHOSPHORUS REMOVING MICROORGANISMS

Even in the early stages of research into excess phosphorus uptake it was recognised that if the phosphorus uptake were biologically-mediated then the storage mechanism would have to be other than that usually attributed to activated sludge bacteria. Levin and Shapiro in their 1965 paper referred to the work of Winkler (1953) in which he noted the capability of bacterial cells to store phosphorus as polyphosphates in a granular form known as volutin. Under circumstances of phosphorus storage the $BOD_5$:phosphorus (or carbon:phosphorus) ratio would not be so process limiting. Two years later Shapiro *et al.* (1967) reinforced this theory by suggesting the presence of a disposable phosphate pool within the sludge microorganisms which would allow the loss or gain of phosphorus without the restriction of high carbon:phosphorus ratios.

At this stage the existence of phosphorus removing microorganisms, in activated sludge, conforming to this scheme was still a matter of speculation. Fuhs and Chen (1975) isolated several strains of bacteria similar to the Acinetobacter-Moraxella-Mima group which were present in phosphorus removing sludge. These bacteria are capable of storing phosphorus as volutin under aerobic conditions and of losing it under anaerobic conditions.

Osborn and Nicholls (1978) carried out further investigations into the volutin polyphosphate storage suggestion. They stated that in Johannesburg pilot plant studies low phosphorus effluents were impossible unless volutin containing bacteria were present. In considering the composition of volutin they suggested in addition to polyphosphate that RNA, lipids, protein and $Mg^{2+}$ could be contained in the granules. These authors also presented a list of volutin containing organisms.

Mino *et al.* (1984) reported on a study of the polyphosphate pool composition of phosphorus removing bacteria. They found that the stored polyphosphate consisted of both low molecular weight polyphosphates and high molecular weight polyphosphates. The low molecular weight polyphosphate was thought to be utilized primarily in the release and uptake cycle while the high molecular weight polyphosphate was considered to function as the phosphorus source for microbial growth.

It now seems likely that the storage of phosphates as high energy polyphosphate chains gives the phosphorus removing bacteria a selective advantage under stress conditions. The energy released in the hydrolysis of the polyphosphate chain can be used by the bacteria for the active transport of substrate across the cell wall during the anaerobic stage. As a result of this, slow growing phosphorus removers such as Acinetobacter can avoid direct competition, in the aerobic stage, with other fast growing aerobes.

The carbon limitation theory of biological phosphorus removal no longer poses a problem in interpretation of the phenomenon. The storage ability for both carbon and phosphorus allows for the manipulation of a favourable ratio. It is also believed that uptake is not strictly metabolic in that the phosphorus may be reserved as an energy source for active transport rather than interacting immediately with the metabolic pathways to form adenosine triphosphate (ATP), the most common bacterial energy carrier.

### 2.4.3 CARBON STORAGE WITHIN PHOSPHORUS REMOVING MICROORGANISMS

Fuhs and Chen (1975) referred to previous, unpublished, results of Chen which showed that carbon, in the internal granular storage product poly-β-hydroxybutyrate (PHB), could provide energy for phosphate accumulation without the immediate need for high carbon:phosphorus ratios. The bacterial isolate, identified as an Acinetobacter ssp, which they believed to be responsible for phosphorus removal was found to have the ability to form PHB.

This finding for phosphorus removing bacteria was repeated by several other researchers (Nicholls and Osborn 1979, Buchan 1983). The ability to store carbon as PHB allows the phosphorus removing bacteria to store the carbon which is transported into the cell during the anaerobic stage. This carbon is then processed through the tricarboxylic acid cycle and electron transportation upon the availability of the terminal electron acceptor, namely oxygen, in the aerobic zone. A typical cycle through the anaerobic/aerobic series initally involves the presence of a large amount of volutin and a small amount of PHB within the bacteria while in the anaerobic zone. The volutin storage product decreases as the polyphosphate chain is broken to provide energy. As the number of single orthophosphate molecules build up a concentration gradient is established across the cell wall. The orthophosphate is then pushed into the surrounding medium. This causes the high orthophosphate concentrations seen in the anaerobic zones of biological phosphorus removal plants. The PHB storage product increases as the transported carbon is stored. In the aerobic zone the stored carbon is utilized and provides the excess energy to allow the uptake and reincorporation into the cell of orthophosphate molecules and the formation of polyphosphate chains. Therefore the amount of PHB decreases and the amount of volutin increases in the aerobic zone.

### 2.4.4 INTERMEDIATE FERMENTATION PRODUCTS

A difference in the metabolic utilization of glucose between phosphorus removing sludge and non-phosphorus removing sludge was reported by Fuhs and Chen (1975). In an experiment with labelled glucose it was found that in the phosphorus removing sludge the Embden-Meyerhof metabolic pathway was utilized whereas in the non-phosphorus removing sludge the Entner-Doudoroff metabolic pathway was prevalent. The Embden-Meyerhof metabolic pathway indicates the presence of facultative anaerobic bacteria and the Entner-Doudoroff pathway is used by aerobic bacteria such as Pseudomonas. Therefore it seemed as if the presence of facultative anaerobic bacteria might be important to the biological phosphorus removal process.

When Fuhs and Chen (1975) isolated bacteria responsible for phosphorus removal they discovered that these bacteria were unable to metabolise sugars or polysaccharides but growth occurred on ethanol and acetate. Ethanol and acetate are products of fermentation and may be produced in an anaerobic environment by facultative and strictly anaerobic bacteria. They also found that if the sludge was kept longer in the laboratory the numbers of Acinetobacter increased. They claimed that this was due to the bacteria using the fermentation products from the anaerobic primary effluent, which was used for feeding.

This led Fuhs and Chen to suggest that the principal function of the anaerobic zone was to promote the presence and growth of facultative anaerobic bacteria. Through a fermentation process these bacteria would produce low molecular weight products such as ethanol or volatile fatty acids such as acetic acid which would serve as carbon sources for the phosphorus removers.

In pilot plant studies Osborn and Nicholls (1978) were able to show that a rapid increase in volutin containing bacteria resulted from the addition of acetic acid. In considering the role of Acinetobacter in phosphorus removal they stated that

> "A basic requirement for the use of Acinetobacter as a control organism is therefore, that a source of low molecular weight organic intermediates must be readily available from a controllable acid fermentation process."

The importance of intermediate fermentation products was also shown by Malnou *et al.* (1984) who found that bacteria in a medium with acetate as the principal source of carbon had phosphorus as 10% to 20% of their dry weight. By comparison similar bacteria on a medium without acetic acid never had greater than 1.5% to 2% dry weight as phosphorus.

Therefore it seems that for phosphorus removing bacteria which are unable to metabolize sugars the availability of low molecular weight fermentation products is a requirement. These products can then be used in energy storage as PHB.

### 2.4.5 BACTERIA ACTIVE IN THE BIOLOGICAL PHOSPHORUS REMOVAL PROCESS

Fuhs and Chen (1975) isolated several of the Acinetobacter genus of bacteria and found them capable of excess phosphorus uptake. They described the bacteria as gram negative aerobes which which were of a short rod shape (0.8 to 1.2μm wide, 1.0 to 1.5 μm long) and nonmotile. All isolates utilized acetate. In further investigation of one isolate it was found that no growth occurred on glucose.

Acinetobacter were found in various full scale plants experiencing excess biological phosphorus removal (Osborn and Nicholls, 1978; Buchan, 1983) and were believed to be primarily responsible for excess uptake of phosphorus. Other investigators showed that when tested with various carbon sources the growth rate on acetate was highest ($\mu_{max}$ = 0.69 $hr^{-1}$) followed by lactate and ethanol, for Acinetobacter 210A (van Groenstijn and Deinema, 1985).

It has been brought into question however whether Acinetobacter is as important to the process as was previously believed, since excellent phosphorus removal has been noted in plants where Acinetobacter are a small fraction of the activated sludge bacteria (Brodisch and Joyner, 1983) and poor removal has been seen where Acinetobacter have been plentiful (Brodisch, 1985). Brodisch (1985) suggested that in order to promote excess biological phosphorus uptake by Acinetobacter a particular bacterium Aeromonas punctata should be present in the sludge. This bacterium produces acetate through fermentation.

The ability of other bacteria to take up phosphorus has been demonstrated (Brodisch and Joyner, 1983; Gersberg and Allen, 1985). However, due to its widespread presence in biological phosphorus removal plants throughout the world, Acinetobacter is still seen as the bacterial genus primarily responsible for biological phosphorus removal. Currently the focus of much research work is on the investigation of interaction and dependence between the phosphorus removers and other bacteria present, notably the facultative anaerobic acid producers.

### 2.4.6 THE EFFECT OF TEMPERATURE ON BIOLOGICAL PHOSPHORUS REMOVAL

Most biological processes are temperature dependent. The temperature dependence of the maximum net specific growth rate of bacteria is shown by the relationship

$$\mu_{max,T} = \mu_{max,20}\ \theta^{(T-20)} \qquad [2.1]$$

T = °C, $\mu_{max,20}$ = maximum specific growth rate, per hour, at 20°C

Since most work in relation to biological phosphorus removal has been done in warm climates such as South Africa the applicability of the process in colder conditions is a concern. While the growth rate of Acinetobacter is definitely affected by colder temperatures some question exists as to whether this is overly detrimental to the process. Working with pure cultures in a phosphate-acetate medium, Fuhs and Chen (1975)found that phosphorus uptake suffered at temperatures below 10°C. Van Groenestijn and Deinema (1985) however found that the phosphorus content of Acinetobacter 210A cells decreased with increasing temperature from 10.1% at 5°C to 1.4% at 33°C. The optimum growth temperature was 25°C.

In pilot plant studies with the A/O™ biological phosphorus removal system Sell *et al.* (1981) found that removal ability increased with sequential decreases in wastewater temperature from 15°C to 5°C. They found that increasing the temperature again impaired the uptake while repeated decrease resulted in improvement to the previous low temperature level. This caused Sell *et al.* (1981) to suggest that the phosphorus removers were psychrophilic.

While it may be possible that the phosphorus uptake ability of the phosphorus removers is not totally restricted at low temperatures concern must be expressed with regard to the ability of the acidogenic bacteria to supply fermentation products as substrate under these conditions. Zoetemeyer *et al.*, (1982), researching temperature effects on separate stage acidification of glucose found two regions of bacterial growth, a mesophilic region and a thermophilic region. The optimum mesophilic temperature was between 36°C and 38°C with a bacterial growth rate of 0.51 $h^{-1}$. By contrast the growth rate at 23°C was reduced to 0.1 $h^{-1}$. The authors also reported deviations in yield of carbon dioxide and hydrogen at temperatures outside the range of 25°C to 55°C. How these results would relate to a situation in which periodic variation between anaerobic and aerobic conditions takes place is unclear however, since the authors were considering anaerobic digestion only.

Gupta *et al.* (1985) reported on a factorial design experiment to evaluate the effects of temperature, retention time and pH control on volatile fatty acid production in an anaerobic environment. They found the best production to occur at six days SRT and a temperature of 30°C. In general they had better VFA production at higher temperatures (30°C vs. 10°C) though it was noted that the interaction levels were significant i.e. the effect of any factor could not be considered in isolation.

Due to the apparent inconsistency reported in the literature it would seem as if this is an area requiring further in-depth research.

## 2.5 BIOCHEMISTRY OF BIOLOGICAL PHOSPHORUS REMOVAL.

### 2.5.1 PHOSPHORUS COMPOUNDS IN MUNICIPAL WASTEWATER

Phosphorus is usually found in domestic wastewater in several forms. The most important of these are the orthophosphates, the polyphosphates and organic phosphates.

The orthophosphate form ($PO_4^{3-}$, $HPO_4^{--}$, $H_2PO_4^-$ and $H_3PO_4$) is the simplest phosphate form and is used directly by bacteria for metabolism. It is also in this form that phosphorus is taken into the cell during excess biological uptake.

Polyphosphates are chains of orthophosphate ranging from two molecule chains to values of $10^6$ molecules. In an aquatic environment polyphosphates will hydrolize to orthophosphate. This hydrolysis under non-catalysed conditions is extremely slow with many years required for the 5% hydrolysis of, for example, pyrophosphate (two molecular chain) at 10°C and pH7 (Snoeyink and Jenkins, 1980). Under conditions of secondary biological treatment this hydrolysis will be enzymatically catalyzed by the bacteria and will progress at a greater rate.

A point of importance with polyphosphates is that they are high energy compounds. The cleavage of the phosphoric anhydride bonds releases energy equivalent to the energy released in the ATP to ADP conversion in bacteria (estimates vary between 7,000 to 10,000 calories/mole).† The formation of polyphosphate chains from orthophosphate molecules may be envisaged as the compressing and locking of a spring. The energy required to do this is stored in the spring and is available for work upon release of the spring. It is the storage and utilization of this type of energy in a polyphosphate pool which is responsible for biological phosphorus removal.

The organically bound phosphorus is not usually considered important in domestic wastewaters as concentrations are typically less than 1 mg/L (Snoeyink and Jenkins, 1980).

### 2.5.2 IMPORTANT ASPECTS OF THE BIOCHEMISTRY OF BIOLOGICAL PHOSPHORUS REMOVAL

In order to better explain some of the current models of biological phosphorus removal a brief description of some of the relevant biochemical terms and concepts will be given initially.

#### 2.5.2.1 ADENOSINE TRIPHOSPHATE

Adenosine triphosphate (ATP), a compound of adenine, ribose and three phosphate groups, is the most important energy carrier within the cellular structure of most life forms. It is a coenzyme, so named for its participation in enzyme catalyzed reactions within the cell. The structure of ATP is such that the anhydride bonds are very labile and release approximately 8 kilocalaries of free energy per mole by hydrolysis. The value of ATP (and the two phosphate form, adenosine diphosphate) to biological systems lies in its ability to supply energy, by hydrolysis of the anhydride bonds, to biochemical reactions which require energy input to proceed. When energy becomes available from energy releasing reactions (exergonic reactions) the ADP molecule is recharged by the addition of a phosphate group to form ATP. This reversible reaction is shown below.

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†The anhydride bond may be considered as the bond resulting from the removal of water from two molecules of phosphoric acid.

$$ATP \leftrightarrow ADP + P_i + 8000 \text{ cal/mole} \qquad [2,2]$$

(Baum, 1970)

### 2.5.2.2 NICOTINAMIDE ADENINE DINUCLEOTIDE

The degradation of substrate in both the fermentative Embden-Meyerhof Pathway and the Krebs Cycle involves the oxidation of the intermediates at various points in the pathways. Each oxidation is half of an oxidation-reduction reaction. Each oxidation involves the loss of electrons from the oxidized species. In order for the reaction to proceed an electron acceptor must be present to take up the electrons i.e. be reduced. In many biological oxidation-reduction reactions the transfer of electrons is simultaneously coupled with the transfer of protons, $H^+$. The transfer is therefore a dehydrogenation (Gaudy and Gaudy, 1980).

One of the most important electron acceptors in biological oxidation-reduction reactions is the compound Nicotinamide Adenine Dinucleotide (NAD) This compound can accept two hydrogen atoms to become reduced $NADH_2$. $NADH_2$ must become reoxidized in order that it be available to accept additional hydrogen in continued substrate metabolism. This is commonly achieved through the Electron Transport Chain in aerobic systems.

### 2.5.2.3 EMBDEN-MEYERHOF METABOLIC PATHWAY

This is a series of reactions utilized in the degradation of glycogen and glucose to pyruvic acid, without the involvement of molecular oxygen. This pathway can be utilized by anaerobic bacteria and aerobic bacteria. The aerobic bacteria will further oxidize the pyruvic acid to carbon dioxide and water, through the Krebs Cycle. Anaerobic bacteria may further degrade the pyruvic acid to ethanol and acetic acid. A net energy increase of two moles of ATP per two moles of glucose can be achieved.

### 2.5.2.4 TRICARBOXYLIC ACID METABOLIC PATHWAY

This is a cyclical series of reactions utilized by aerobic bacteria, in the presence of oxygen, for the oxidation of various substrates which enter the cycle as acetyl-CoA (i.e. acetyl-coenzyme A). The tricarboxylic cycle (TCA), or Krebs Cycle, represents complete oxidation of the substrate and gives a net energy increase of thirty eight moles of ATP per mole of glucose (i.e. with the EM pathway energy release included). This is represented as

$$C_6H_{12}O_6 + 6\ O_2 + 38\ ADP + 38\ P_i \rightarrow 6\ CO_2 + 6\ H_2O + 38\ ATP \quad \text{(Baum, 1970)} \qquad [2.3]$$

### 2.5.2.5 ELECTRON TRANSPORT CHAIN

In order that $NADH_2$ be made reavailable for electron acceptance its two hydrogen atoms must be transferred to another compound. In respiring cells the electrons are transferred through a series of compounds by a process of reduction and reoxidation. This transfer continues until the electrons are passed to a *terminal electron acceptor* such as oxygen. These compounds form the Electron Transport Chain in bacteria.

### 2.5.2.6 PROTON MOTIVE FORCE

The electron transport system is believed to be situated asymmetrically within the cellular membrane of bacteria (Brock *et al.*, 1984). At one point in the electron transport chain the two electrons and protons are separated. The two protons (or hydrogen ions) are ejected from the cell. The electrons combine with two protons, which become available from the dissociation of two water molecules from the bacterial cytoplasm. The hydrogen molecules combine with oxygen as the terminal electron acceptor to form one molecule of water. This causes a net production of $OH^-$ ions inside the cell. This is demonstrated in Equations 2.4 and 2.5.

$$2H_2O \leftrightarrow 2H^+ + 2OH^- \qquad [2.4]$$

$$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \leftrightarrow H_2O \qquad [2.5]$$

Since the membrane is not freely permeable to $OH^-$ or $H^+$ a pH gradient and an electrical potential are generated across the membrane by the $H^+$ ions on the outside and the $OH^-$ on the inside. This potential is known as the Proton Motive Force.

The energy stored by the proton motive force can be utilized in the production of ATP in a reversible reaction catalysed by the enzyme ATPase.

### 2.5.3 ACETIC ACID FORMATION IN THE ANAEROBIC ZONE

Gaudy and Gaudy (1980) show a possible pathway in which the fermentation products acetic acid and ethanol may be formed in the anaerobic zone by E.coli and other enteric bacteria. The pathway involves a breakdown of glucose to pyruvic acid through the Embden-Meyerhof Pathway followed by breakdown through various intermediates to ethanol and acetic acid. The complete pathway represents a gain in energy to the organism through the synthesis of five moles of ATP per two moles of glucose.

### 2.5.4 UTILIZATION OF ACETIC ACID AS SUBSTRATE

The utilization of the EM pathway by microbes is sometimes allowed to progress only to an intermediate stage. The intermediates formed are withdrawn from the pathway and used in biosynthesis reactions. This happens only in enough instances to provide the building materials for the cell, otherwise oxidation to pyruvate will occur. Similarly in the Krebs Cycle intermediates may be withdrawn for biosynthesis. This presents a problem however since removal of intermediates will interupt the cycle and prevent the resynthesis of oxaloacetate which is necessary for the reinitiation of the cycle.

In bacteria which utilize acetate as substrate the acetate is firstly converted to acetyl-CoA. The acetyl-CoA then enters a form of the Krebs Cycle known as the Glyoxalate Cycle (or Bypass). This form allows for the withdrawal of several intermediates for biosynthesis while still maintaining the cycle. An extra molecule of oxaloacetate is also formed which can be enzymatically reverted to phosphoenolpyruvic acid (PEP). PEP can then be used in a reversal of the EM pathway which can provide those EM intermediates necessary for biosynthesis.

This is necessary since the acetic acid users are unable to utilize glucose through the EM pathway and therefore the intermediates would otherwise be absent. For a more detailed discussion of these points the reader is referred to "Microbiology for Environmental Scientists and Engineers." by Gaudy and Gaudy, 1980.

### 2.5.5 FORMATION OF THE PHB STORAGE PRODUCT

PHB, a storage product in bacteria, may be compared to fat as a storage product in humans. This internal store of carbon is built up when external carbon sources are easily available (i.e. preferentially available to the phosphorus removers). The breakdown of PHB does not usually occur until other available carbon sources are scarce.

### 2.5.6 POLYPHOSPHATE FORMATION AND STORAGE WITHIN THE BACTERIAL CELL

While biological phosphorus removal has been observed for a period in excess of twenty years knowledge about the internal biochemical mechanisms which bring about the uptake and storage is still limited and theories still remain speculative. The observation of dense polyphosphate storage granules within the bacterial cells of phosphorus removers has led researchers to consider the process of internal polyphosphate formation and degradation.

Several workers have suggested that the only mechanism active in polyphosphate formaton is the transfer of the terminal phosphoric group of ATP to a polyphosphate chain. This relationship is expressed below.

$$(P_i)_n + ATP \leftrightarrow (P_i)_{n+1} + ADP \qquad [2.6]$$

The enzyme which can catalyze this reversible reaction, in principle in either direction, was isolated by Kornberg and his co-workers and termed polyphosphate kinase (Kornberg *et al.*, 1956; Kornberg, 1957). Kulaev (1979) stated that polyphosphate synthesis is strongly inhibited by ADP i.e. at high ADP/ATP ratios the reaction will shift to the left causing a degradation of the polyphosphate in favour of ATP formation. Mino *et al.*, (1985), claimed that the orhthophosphate pool must be considered as the source of ATP production.

Contrary to this scheme however is the finding of polyphosphate biosynthesis by enzyme systems other than polyphosphate kinase (Kulaev, 1979). Whichever system is at work it seems as if the phosphorus removers have the advantage of elevated phosphorus and energy storage. The manner in which the polyphosphate chain is combined with the various other components of volutin is uncertain but it does not appear to affect the examination of polyphosphate as an isolated molecule. The hydrolysis of the polyphosphate pool is represented below (Kulaev, 1979; Gaudy and Gaudy, 1980)

$$(P_i)_n + H_2O \rightarrow (P_i)_{n-1} + H_3PO_4 \qquad [2.7]$$

This reaction is catalyzed by the enzyme polyphosphatase. While this could account for the polyphosphate pool as a source of phosphorus it is not immediately clear whether in the hydrolysis of the high-energy anhydride bond the energy released is utilized or dissipated. Kulaev, (1979), believed it unlikely that the energy stored would not be utilized. He suggested that hydrolysis might not immediately go to orthophosphate but might involve the transfer of phosphate, without the loss of energy from the high-energy bond, to an intermediate labile phosphorus compound which might undergo further hydrolysis to orthophosphate while also utilizing the available energy.

A possibility which allows for the usage of the stored energy is that the reversal of Equation 2.2 takes place, forming ATP. This ATP may then in turn be utilized in the activation of acetate. This may be expressed as

$$\text{Acetate} + \text{CoA} + \text{ATP} \rightarrow \text{Acetyl-CoA} + \text{AMP} + 2P_i$$

AMP = Adenosine Monophosphate [2.8]

The acetyl-CoA formed in Equation 2.8 may then be utilized in the synthesis of PHB. The pyrophosphate group may then undergo hydrolysis and ejection from the cell. Kulaev (1979) also reported the usage of liberated energy in the active transport of sugars in Neurospora crassa. This possibility will be discussed in a later section. Whatever the reason for phosphorus storage the polyphosphate form is convenient since it will have little effect on the osmotic pressure within the cell as would ATP or orthophosphate (Harold, 1966).

In summary, the phosphorus removers which are unable to metabolize sugars will depend on facultative anaerobic bacteria to produce short chain fatty acids, such as acetic acid, as substrate. The phosphorus removers can then metabolize the acetate. Storage of carbon as PHB can then take place. In aerobic conditions breakdown of the PHB can occur providing energy for ATP formation and polyphosphate synthesis by Equation 2.6.

Phosphorus removers which metabolize sugars will obtain energy for polyphosphate synthesis along the normal metabolic pathways.

## 2.6 MODELS OF THE BIOLOGICAL PHOSPHORUS REMOVAL PROCESS.

### 2.6.1 HEURISTIC MODELS

Several heuristic models have recently been fitted to various phosphorus removal data sets in an attempt to find a reliable method of phosphorus removal prediction (Hong *et al.*, 1981; Siebritz *et al.*, 1983; Câmara *et al.*, 1985). These models appear, for the most, to have been developed from process and site specific data and their universal applicability still remains to be verified. Note that due to the large number of symbols and abbreviations used in this section definition of these within the text was not considered appropriate. A separate listing of symbols and abbreviations, with explanations, is presented elsewhere in this thesis.

#### 2.6.1.1 A/O MODEL

This model presented by Hong *et al.*, (1981), results from the authors' experience with pilot and full scale A/O™ systems in the United States. The model incorporates the principle of internal polyphosphate degradation in order to provide energy for the active transportation of substrate into the bacterial cell.

In the anaerobic section the depletion of soluble BOD is attributed to bacterial absorption and denitrification reactions. At the same time soluble BOD formation is caused by the hydrolysis of biodegradable solids and the lysis of biomass.

Two differential equations, reflecting phosphorus release and phosphorus uptake are presented. These are Equations 2.9 and 2.10 respectively.

$$\frac{dPS}{dt} = K_1\left(\frac{h_1PI}{X} - PS\right)X + h_2R_{BOD} \qquad [2.9]$$

$$\frac{dPS}{dt} = K_2 \; X \; PS \; \left(\frac{1-PI/P^*}{K_s + 1 - PI/P^*}\right) \qquad [2.10]$$

Equation 2.9 presents phosphorus release as a function of an internal-external phosphorus gradient and soluble BOD (shown as BODS) uptake. Since the soluble BOD uptake rate must depend on a fairly complex BODS balance (as indicated above) it would seem unlikely that the BOD uptake could be adequately measured in the form of the second term of Equation 2.9, i.e., as a constant times a varying BODS uptake rate.

The phosphorus uptake is considered to be first order in the soluble phosphorus and the active biomass, moderated by the fraction of available polyphosphate storage capacity utilized and the saturation constant $K_s$. Model constants evaluated from pilot plant data at a soluble substrate to microorganism mass, as VSS, ratio, i.e., $F_s/M$ ratio of 0.34 were applied to a full scale plant operating at an $F_s/M$ ratio of 0.12. The authors claim the effects of scale to be unimportant and that

F/M effects are correctly incorporated in the model form.

### 2.6.1.2 RAPIDLY BIODEGRADABLE COD MODEL

This model due to Siebritz *et al*. (1983) is based on the usage of a propensity factor, $P_f$, as a measure of the likelihood of excess phosphorus removal under a given set of conditions. The propensity factor is defined as the product of three terms, any of which, according to the authors, when equal to zero will cause a complete lack of excess phosphorus removal. Thus a value equal to or less than zero for the propensity factor is claimed to result in lack of removal. The three terms are, the anaerobic reactor rapidly biodegradable COD concentration in excess of 25 mg/L, $(S_{bsa} - 25)$, the actual anaerobic detention time, $R_{an}$ and the fraction of the total mass of sludge in the process passing through the anaerobic reactor per day, n.

Through some mathematical and definitional manipulation the expression for the propensity factor is reduced to Equation 2.11.

$$P_f = (S_{bsa} - 25)f_{xa} \qquad \text{(mg COD/L)} \qquad [2.11]$$

$f_{xa}$ = anaerobic sludge mass fraction

Therefore the likelihood of excess phosphorus uptake is presented as a function of the rapidly biodegradable COD in excess of 25 mgCOD/L in the anaerobic reactor and the magnitude of the anaerobic mass fraction. This expression was derived for a process configuration known as the UCT process but modification should be possible for other process layouts.

The authors also presented an expression for the magnitude of the excess phosphorus removal. This is shown in Equation 2.12.

$$\Delta P_s = \left(\frac{1 - f_{us} - f_{up}}{1 + b_{hT} R_s}\right)(\gamma + f_p \; f \; b_{hT} \; R_s) + \frac{f_p \; f_{up}}{P_v} \qquad [2.12]$$

This model has met with some opposition, notably from Barnard, (1983a), and Roberts, (1983). The authors however claim predictive succcess with its use in a laboratory scale UCT process.

### 2.6.1.3 STOICH MODEL

The STOICH model, a computerized method, is due to Câmara *et al.*, (1985). The authors cite the work of Sherrard and Schroeder as showing that phosphorus removal in an activated sludge plant depends on the net solids production and that the efficiency of this removal is related to the wastewater stoichiometry. Since the solids production is a function of the mean cell residence time (MCRT) the authors compare orthophosphate removal with MCRT.

On the basis of the Lawrence and McCarty wastewater treatment model and the influent wastewater composition the STOICH model calculates the expected phosphorus removal effficiency. The authors do not indicate whether any level of practical success has been achieved with this model however.

### 2.6.2 MECHANISTIC MODELS

Very few models which attempt to explain the excess biological phosphorus removal phenomenon within the framework of biological and biochemical mechanisms have been proposed. One of the most recent and comprehensive is the biochemical model of Comeau *et al.*, (1985).

#### 2.6.2.1 BIOCHEMICAL MODEL OF BIOLOGICAL PHOSPHORUS REMOVAL

The overall model is postulated in two halves, that of aerobic conditions and that of anaerobic conditions (Comeau *et al.*, 1985). The authors suggest that under aerobic conditions oxygen will be available as a terminal electron acceptor. Therefore proton expulsion from the cell will occur as a result of electron chain transport. This will aid in the generation and maintenance of the proton motive force. The energy released in oxidation through the Krebs Cycle will be stored by means of ATP, which will be formed through the proton motive force, a process known as electron transport phosphorylation.

The ATP/ADP ratio would then be expected to increase thereby stimulating the formation of polyphosphates in the phosphorus removing bacteria (Kulaev, 1979). As external carbon sources become more limited breakdown of the stored PHB would be expected to commence.

In applying the model to anaerobic conditions Comeau *et al.* (1985) consider acetic acid as the substrate to be utilized by the phosphorus removers. They assume that the small percentage of undissociated acetic acid (quoted as 1% of acetic species at pH 6.5) is transported neutrally across the bacterial membrane under conditions of internal-external pH gradient. The energy required for this active transport may come from the cell's polyphosphate pool.

Internal dissociation of the acetic acid is then assumed to take place. The liberation of one proton per molecule of acetic acid will reduce the proton motive force. This situation is intolerable to the cell since bacteria try to maintain a constant proton motive force (Brock *et al.*, 1984). Also in view of the postulated transport mechanism a reduction in pH gradient would prevent further substrate uptake.

For normal aerobes under aerobic conditions there are several ways in which the proton motive force may be regenerated. Three mechanisms are quoted and discounted by the authors. The first is respiration followed by electron transport phosphorylation. This will only occur in the presence of a terminal electron acceptor. The second method involves ATPase reaction reversal i.e. ATP → ADP with consequent $H^+$ expulsion. This cannot occur however since depletion of ATP cannot be refurbished through substrate level phosphorylation (the formation of ATP in the EM pathway) since acetate is the substrate. The third mechanism is that of $NADH_2$ reduction and electron chain transportation catalyzed by a membrane bound enzyme, transhydrogenase. This is dismissed on the grounds of efficiency reduction in substrate storage which would result.

Therefore it would seem as if the uptake of acetic acid causes an impossible situation for the bacterial cell. The authors in the most significant innovation of their argument postulate the presence of a pH gradient sensitive translocating enzyme within the bacterial membrane. In a situation of low pH gradient this enzyme would activate a phosphorus carrier protein which would transport either protonated polyphosphates or protonated orthophosphates from the cell. The free phosphates would be readily available from the polyP-ATP-active transport system. Thus the internal build-up of phosphates would be relieved and regeneration of the proton motive force would occur. When a sufficient pH gradient exists the translocation enzyme would not be active.

This model, while somewhat speculative in the existence of the translocation enzyme, fits the release-uptake and acetate utilization observations very well. At the same time it pays due observance to accepted biochemical and microbiological theory.

## 2.7 OXIDATION-REDUCTION POTENTIAL

Oxidation-reduction potential (ORP) was first investigated in relation to biological phosphorus removal by Shapiro *et al.* (1967). In experiments with sludge from the City of Baltimore activated sludge unit they noticed an apparent correlation between falling ORP and orthophosphate release in sealed batch containers. They found that phosphorus release seemed to correspond more to falling ORP than to dissolved oxygen depletion. Release failed to occur, even when the dissolved oxygen probe registered zero, when the ORP remained at levels greater than about 150 mV (Calomel reference). The rate of release was reported to increase further when the ORP reached zero. Upon reaeration the phosphorus uptake was found to respond not to the increase in dissolved oxygen but to the increase in ORP which lagged several minutes behind.

In contrast Randall *et al.* (1970) dissented from this opinion and claimed, on the basis of experimental work, that phosphorus release was the cause of falling ORP rather than a consequence of it. They based this on the fact that in their experiments ORP almost always followed phosphorus release and never preceded it.

Koch and Oldham (1985) provided further insight into the usage of ORP in the anaerobic zone of biological phosphorus removal plants. In measuring the decrease in ORP in batch anaerobic reactors they noticed that the decrease accelerated at two separate discernable points on the ORP-time curve. The first breakpoint was shown to correspond to the disappearance of dissolved oxygen from the reactor. The ORP at which this breakpoint occurred varied, however. In general it fell between +100 mV and +200 mV, Ag/AgCl reference (+55 mV and +155 mV, Calomel reference). This rate of ORP decrease was noted to continue until a further acceleration took place, typically between -40 mV and -140 mV, Ag/AgCl reference (-85 mV and -185 mV, Calomel reference). This breakpoint was found to correspond to the disappearance of nitrates from the reactor (i.e. the cessation of denitrification). They showed phosphorus release as occurring at or just prior to this breakpoint.

The authors observed that the data agreed well with the prediction of equilibrium theory which under the particular experimental conditions predicted the disappearance of nitrate nitrogen from the system at an ORP of about -70 mV, Ag/AgCl reference, (-115 mV, Calomel reference).

These findings are significant in that they give a method of discerning the level of biological activity present in the anaerobic reactor. The authors suggest that prior to the first breakpoint, aerobic respiration occurs (obviously in an anaerobic reactor this should be virtually absent). After the first breakpoint, respiration utilizing combined oxygen, such as $NO_3^-$ from the return sludge, as a terminal electron acceptor should take place. After the second breakpoint totally anaerobic conditions exist and fermentation should be the only activity.

Since phosphorus release is believed to take place only in the absence of nitrates (Barnard, 1974) the ORP should remain below the second breakpoint. Unfortunately due to the reported variance of its location this may be difficult to monitor.

The findings of Koch and Oldham (1985) may go some way towards explaining the lag between dissolved oxygen disappearance and phosphorus release noted by Shapiro *et al.* (1967). The possibility of the absence of free oxygen with the continued presence of nitrate exists. The completion of denitrification and the consequent ORP reduction may then have resulted in the phosphorus release.

To date there exists very little investigative research into ORP as applied to biological phosphorus removal beyond the correlation between low ORP and phosphorus release noted by Shapiro *et al.* (1967). While ORP is unlikely to act as a quantitive predictive measurement it is of some consequence in ascertaining the ability of the anaerobic reactor to promote biological phosphorus release. It is through this characteristic that it may find use in biological phosphorus removal plants.

## 2.8 ALTERNATE THEORY OF EXCESS PHOSPHORUS REMOVAL

Menar and Jenkins (1969) proposed that the excess phosphorus removal reported by Levin and Shapiro (1965) and others was the result of a cationic-phosphate precipitation within the activated sludge floc. In hard waters this would take the form of calcium phosphate.

They suggested that since dissolved oxygen consumption at the head end of a conventional activated sludge plant is very high the carbon dioxide production would also be very high, as a result of organic matter metabolism. The high carbon dioxide production would cause a high carbon dioxide concentration in the mixed liquor. This in turn would result in a low mixed liquor pH. Menar and Jenkins suggested that under conditions of dissolved oxygen depletion and low pH, solubilization of calcium phosphate compounds would occur.

This would occur especially within the floc matrix since within the interstitial fluid conditions of pH depression greater than that in the external medium were possible. As a result elevated phosphorus concentrations were to be expected within the head end of the aeration tank, or under anaerobic conditions.

As the mixed liquor moved through the basin a point of lesser available organics, coupled with a decrease in carbon dioxide production, would be reached. At this point an increase in mixed liquor pH would be expected. The available calcium and phosphorus would then precipitate within the floc and be carried from the system within the waste activated sludge.

Other factors which would aid the proposed process were the hydrolysis of the influent polyphosphates and the microbial degradation of fatty acid calcium salts, thus making available even more precipitate constituents.

Research by various workers which showed that process depression could be achieved by the addition of bacterial inhibitors weakened the idea that the removal was due exclusively to a chemical precipitation mechanism (Levin and Shapiro, 1965; Shapiro, 1967; Yall *et al.*, 1970). It appeared as if the process removal was at most a biologically mediated precipitation mechanism. Doubt was even cast on this however by the cation balances which formed part of the results of further research (Vacker *et al.*, 1967; Yall *et al.*, 1970; Simpkins and McLaren, 1978; Kainrath *et al.*, 1985).

Arvin (1983), in a review of the literature, stated biological phosphorus removal to be a combination of several mechanisms, biological and chemical. The biological mechanisms were normal phosphorus assimilation for life processes and polyphosphate accumulation as a result of aerobic/anaerobic cycling. The chemical mechanisms included normal bulk precipitation, stimulated by a pH greater than 7.5 and high $Ca^{2+}$ concentrations. Accelerated bulk precipitation, also requiring these conditions but driven by the high phosphorus conditions resulting from anaerobic release was also noted. Chemical precipitation within the biofilm due to denitrification, an alkalinity producing process (Arvin and Kristensen, 1983), was listed.

Therefore it would seem as if the major part of excess phosphorus removal is a result of biological uptake. A concurrent biologically mediated chemical precipitation mechanism can also be considered to be active in removal. The effectiveness of this mechanism seems strongly dependent on the wastewater characteristics.

## 2.9 PROCESS CONFIGURATIONS USED IN EXCESS BIOLOGICAL PHOSPHORUS REMOVAL

Since the inception of purpose built biological phosphorus removal plants by Levin *et al*., (1972) many different designs have been utilized, both in research and full scale practice. If the number of retrofitting options are included a staggering number of configurations have evolved. Because of this it is becoming increasingly difficult to be comprehensive in any examination of the possible processes for biological phosphorus removal. Therefore only a brief synopsis will be attempted here.

### 2.9.1 THE PHOSTRIP PROCESS

Levin *et al*. (1972) introduced the PhoStrip process which was the first activated sludge process designed specifically for biological phosphorus uptake. The configuration is shown in Figure 2.1. The process utilizes the phenomena of phosphorus release under anaerobic conditions and the improved uptake which follows this stripping. The basic process involves the uptake of phosphorus in the aeration tank and is affected by the conditioned sludge. The low phosphorus effluent is then discharged. The high phosphorus sludge is removed from the secondary clarifier to an open tank similar to a gravity sludge thickener. In this tank the conditions become anaerobic with a consequent release of phosphorus. The sludge continues to settle leaving a phosphorus rich supernatant. This supernatant is removed and subjected to chemical (usually lime, CaO) precipitation treatment in order to remove the phosphorus. The phosphorus stripped sludge is removed from the bottom of the thickener and returned to the head of the aeration tank where the process cycle begins again.

The PhoStrip process makes use of a combination of chemical and biological treatment. However from pilot plant studies Levin *et al.* (1973) reported that addition of lime to the phosphorus-rich supernatant alone at a dose of 300 mg/L (equivalent to 24 mg/L in the total wastewater flow) produced a 95% phosphorus removal, a treatment equivalent to that produced by dosing the total wastewater flow at 300 mg/L. This represents a dose reduction of 92%. A split-flow return sludge modification to the process was reported by Topol *et al.* (1974). In this configuration only a portion of the return sludge from the secondary clarifier goes through the phosphorus stripping tank. In pilot plant tests in Maryland and Chicago sustained removals of 90% were attained. This modification was claimed to reduce both the chemical dosage and the size requirement of the phosphorus stripper tank.

Further modifications were later added to the process. These include the provision of an anoxic tank for denitrification of return sludge, from a nitrifying system, before it enters the stripper tank. Another addition was a system to allow recirculation of the phosphorus stripped sludge and or elutriation of the sludge in the stripper tank with primary effluent. The recycle facility in the phosphorus stripper tank allows dilution of phosphorus released within the sludge with the low phosphorus-containing liquid in the tank feed. The dissolved phosphorus then moves more easily to the tank surface and ensures a higher phosphorus removal with the supernatant. To induce a rapid release of phosphates from the phosphorus-rich bacteria the availability of a carbonaceous substrate, such as acetate, is of advantage. This stimulates carbonaceous uptake and phosphate release in accordance with a previously discussed mechanism. A disadvantage of a side stream process such as PhoStrip is the complete reliance on endogenous respiration to provide the carbon source within the phosphorus stripper (Barnard, 1983b; Paepcke, 1985). Endogenous respiration alone may not be able to meet the carbonaceous demand.

It is for this reason that the modification of primary effluent addition was introduced. A second advantage of this addition is the elutriation of solids in the bottom of the stripper tank and the transport of the released phosphorus to the surface supernatant (Miyamoto-Mills *et al.* ,1983). The side stream process does have the advantage that it is protected from variations in influent quality. The PhoStrip process has been recognised as a reasonable method of phosphorus control and to that end it has been implimented in fourteen full-scale plants in the United States (Paepcke, 1985).

### 2.9.2 THE BARDENPHO PROCESS

The original Bardenpho nutrient removal system as introduced by Barnard (1974) is shown in Figure 2.2. This is a four stage process in which influent carbonaceous substrate provides a carbon source which is utilized by denitrifying bacteria, in the primary anoxic zone, to remove nitrates from the influent wastewater and the nitrified mixed liquor recycle. Any nitrified liquor which escapes recycle to the primary anoxic reactor undergoes denitrification in the secondary anoxic reactor, with endogenous respiration providing the carbon source.

A final reaeration reactor is constructed after the secondary reactor. Barnard (1974) gave the reasons for its inclusion as

1. To strip carbon dioxide from the mixed liquor in order to raise the pH thus facilitating easier phosphorus precipitation.
2. To raise the dissolved oxygen concentration of the mixed liquor to a sufficient level to prevent further denitrification in the clarifier.
3. To prevent release of phosphates to the liquid in the clarifier.
4. To condition the mixed liquor solids for good sedimentation.

This system, which was designed primarily for nitrogen control, removed up to 97% of the influent phosphorus to the original pilot plant. This removal occurred between the

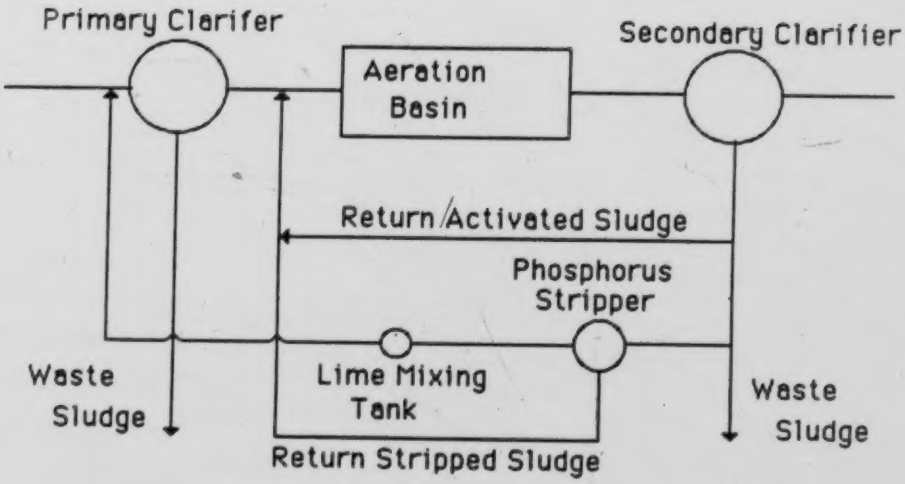

Primary Clarifer
Aeration Basin
Secondary Clarifier
Return Activated Sludge
Phosphorus Stripper
Waste Sludge
Lime Mixing Tank
Waste Sludge
Return Stripped Sludge

Figure 2.1 The PhoStrip Process

third and final basins. During periods of good phosphorus removal the phosphorus concentration in the secondary anoxic basin reached a level in excess of 30 mg-P/L. Influent concentrations ranged between 9 mg-P/L and 12 mg-P/L. The effluent concentration was reduced to 0.3 mg-P/L. These results were achieved only when nitrate removal was also good. In this situation any nitrates from the primary aerobic basin were quickly removed in the secondary anoxic basin which would then become anaerobic enough to promote phosphorus release.

### 2.9.3 THE PHOREDOX PROCESS

This process configuration consists of a five stage process in which an anaeobic basin is placed immediately before the Bardenpho process. Some confusion exists with regard to the nomenclature applied to this configuration. The original Phoredox (from phosphorus and redox potential) name referred to the addition of the anaerobic basin (Paepcke, 1985). In South Africa, however, where the process was developed, the name came to be applied to the complete process.

This five stage process is sometimes referred to as the Modified Bardenpho Process or even as the Bardenpho Process. The process as used for denitrification and phosphorus removal is shown in Figure 2.3. In this system, release is encouraged in the first basin with uptake following in the primary aerobic basin. Simultaneous nitrogen removal will take place, mostly between the second and third basins. In fact in some cases it was found that the secondary anoxic and aerobic tanks added so little to the system that they were often removed from the process, a configuration termed the Modified Phoredox Process (Figure 2.4). The Phoredox system can also be used in a modified form for phosphorus removal when nitrogen removal is not required.

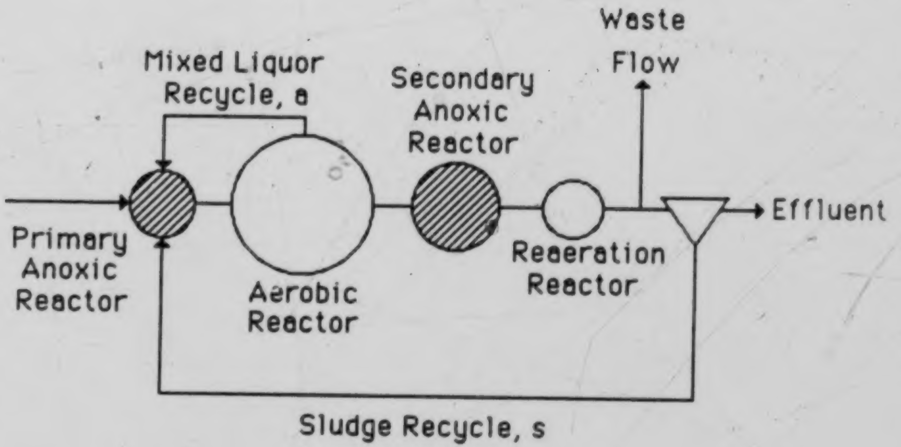

Waste
Flow
Mixed Liquor
Recycle, a
Secondary
Anoxic
Reactor
Effluent
Primary
Anoxic
Reactor
Aerobic
Reactor
Reaeration
Reactor
Sludge Recycle, s

Figure 2.2 The Bardenpho Process

### 2.9.4 THE UCT PROCESS

A potential problem with the Phoredox Process was the possibility of a high degree of nitrate return in the return sludge. Thus the required level of anaerobiosis would not be possible in the anaerobic basin. Phosphorus release would not occur and therefore uptake would be upset.

Siebritz *et al.* (1983) noted further South African research, principally at the University of Cape Town, which produced a proposal for the configuration shown in Figure 2.5. This system was termed the UCT Process. It resulted from study of the Phoredox configuration. Researchers, such as Maris, Siebritz and Ekama, as reported by Siebritz *et al.* (1983), found that the anoxic zones could not, per se, be increased in order to reduce the effluent and underflow nitrate concentrations. They found that in increasing the unaerated mass fraction, for a particular sludge age and temperature, the nitrification process stopped. They claimed that the maximum allowable anoxic mass fraction was related to the specific growth rate of the nitrifiers.

In modelling the process Siebritz *et al.* (1983) concluded that the Phoredox process could achieve complete nutrient control only if the TKN/COD ratio were below 0.08. Siebritz *et al.* (1980) attempted to make the anaerobic reactor independent of the degree of nitrification. In diverting the return sludge to the first anoxic reactor and recycling mixed liquor to the anaerobic basin Siebritz *et al.* (1983) claimed that by control of the anaerobic / anoxic

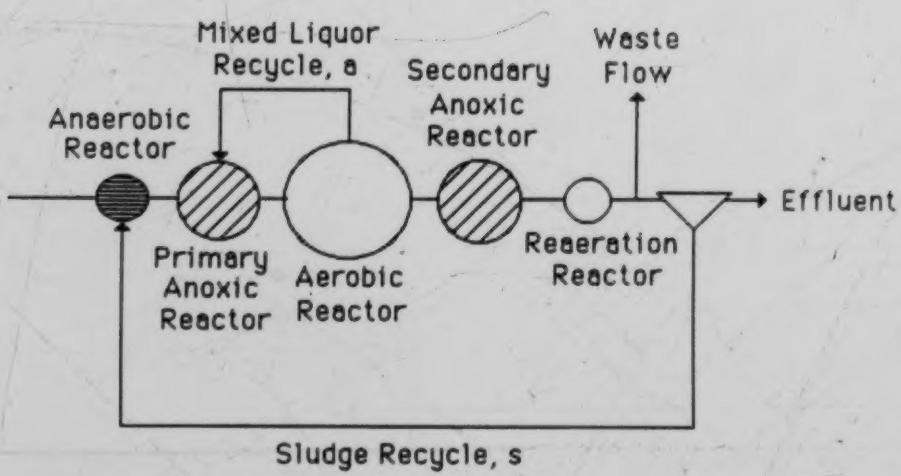

Mixed Liquor
Recycle, a
Secondary
Anoxic
Reactor
Waste
Flow
Anaerobic
Reactor
Effluent
Primary
Anoxic
Reactor
Aerobic
Reactor
Reaeration
Reactor
Sludge Recycle, s

Figure 2.3 The Phoredox Process.

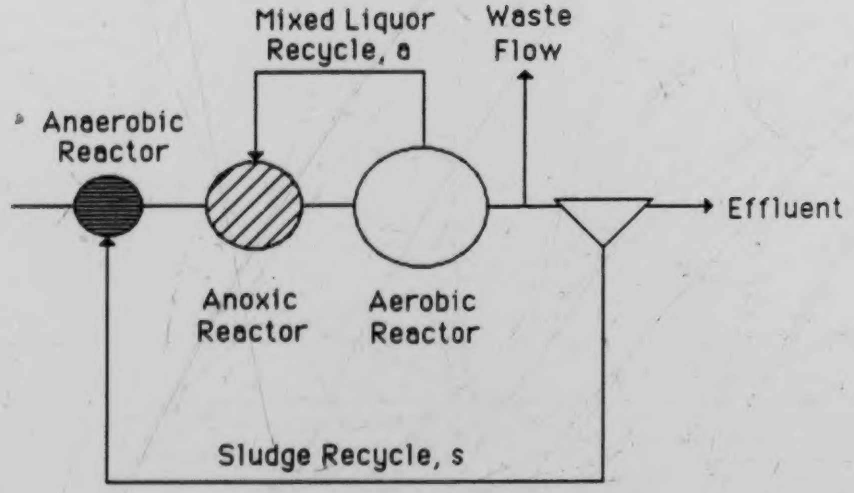

Mixed Liquor
Recycle, a
Waste
Flow
Anaerobic
Reactor
Effluent
Anoxic
Reactor
Aerobic
Reactor
Sludge Recycle, s

Figure 2.4 The Modified Phoredox Process.

mixed liquor recycle the anoxic reactor nitrate could be reduced to almost zero and therefore the anaerobic reactor received a nitrate free recycle regardless of the aerobic reactor and effluent nitrate concentrations. The second anoxic basin and the final aerobic basin were removed. Siebritz *et al*. (1983) reported the effectiveness of this system with an influent TKN/COD ratio of up to 0.14 mg N/mg COD.

In order to prevent overloading of the denitrification capability of the anoxic reactor under conditions of high nitrogen loading (high TKN/COD ratio) the mixed liquor recycle a shown in Figure 2.5 can be decreased. A problem arose with this system however in that reducing recycle a caused an increase in anoxic detention time beyond one hour. This seemed to adversely affect the settleability of the mixed liquor solids (Siebritz *et al*., 1983) By splitting the anoxic reactor into two as shown in Figure 2.6 it was not necessary to change the mixed liquor recycle a when the TKN/COD ratio increased and the MLSS were not retained longer than one hour within the anoxic stage.

### 2.9.5 THE A/O PROCESS

The A/O™ process, as reported by Hong *et al.* (1981), is a staged anaerobic/aerobic system developed by Air Products and Chemicals, Inc. in the United States. Both the anaerobic and aerobic sections are divided into interconnected compartments. These are individually mixed or aerated. The return sludge is mixed with the influent wastewater prior to entry into the anaerobic zone. The concept is similar to the Phoredox system of Barnard and likewise can be operated for complete nutrient removal or for the removal of phosphorus only. These options are shown in Figures 2.7 and 2.8, respectively. Currently there are two full scale A/O plants in the U.S., at Pontiac, Michigan and Largo, Florida (Paepcke, 1985)

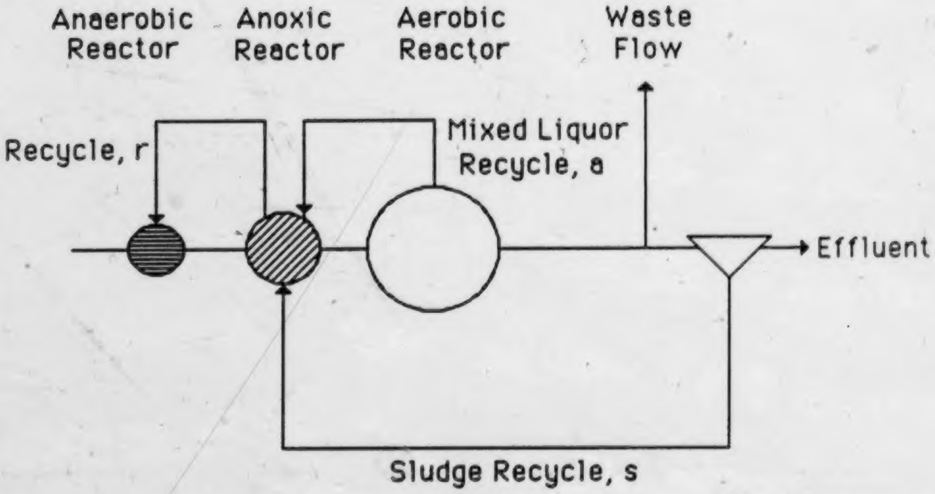

Anaerobic Reactor
Anoxic Reactor
Aerobic Reactor
Waste Flow
Recycle, r
Mixed Liquor Recycle, a
Effluent
Sludge Recycle, s

Figure 2.5 The UCT Process

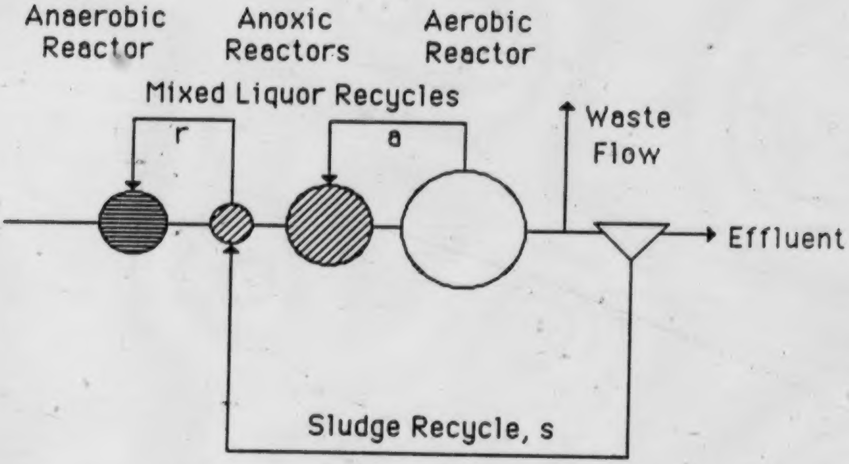

Anaerobic Reactor
Anoxic Reactors
Aerobic Reactor
Mixed Liquor Recycles
r
a
Waste Flow
Effluent
Sludge Recycle, s

Figure 2.6 The Modified UCT Process

### 2.9.6 THE BIODENIPHO PROCESS

This process, which involves a combination of batch and continuous treatment, has been developed in Denmark (Arvin and Kristensen, 1985). The treatment sequence involves one hour anaerobic, one hour anoxic, one hour aerobic and one hour of sedimentation. The Biodenipho Process is an extension of a previous similar process, the Biodenitro Process, developed for nitrogen removal (Bundgaard *et al.*, 1983).

While about ten full scale Biodenitro plants are currently in operation in Denmark (Paepcke, 1985) the only application of the Biodenipho system seems to be at pilot scale at the Technical University of Denmark (Arvin and Kristensen, 1985).

### 2.9.7 SEQUENCING BATCH REACTORS

A sequencing batch reactor (SBR) system for biological phosphorus removal has been used with success at the University of Notre Dame (Manning and Irvine, 1985). An eight hour cycle consisting of a two hour fill period, a four hour aeration period, a one hour settling period and a one hour draw or decant period was used. A liquid volume of 3.6 litres after fill and 1.2 litres after draw with a six to seven day sludge age was used. Using this system and various combinations of fill and mixing, a phosphorus reduction from 13 mg-P/L to less than 0.5 mg-P/L was achieved. The authors make no reference to any large scale

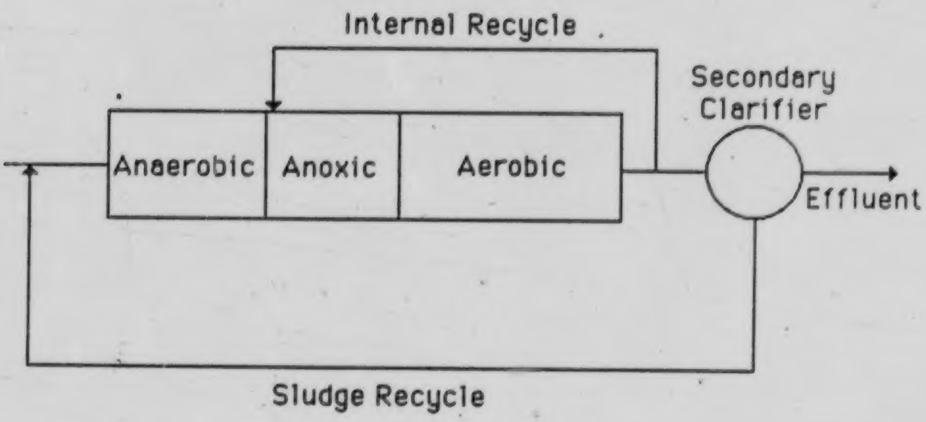

Internal Recycle
Secondary Clarifier
Anaerobic
Anoxic
Aerobic
Effluent
Sludge Recycle

Figure 2.7 The A/O Process for Complete Nutrient Removal.

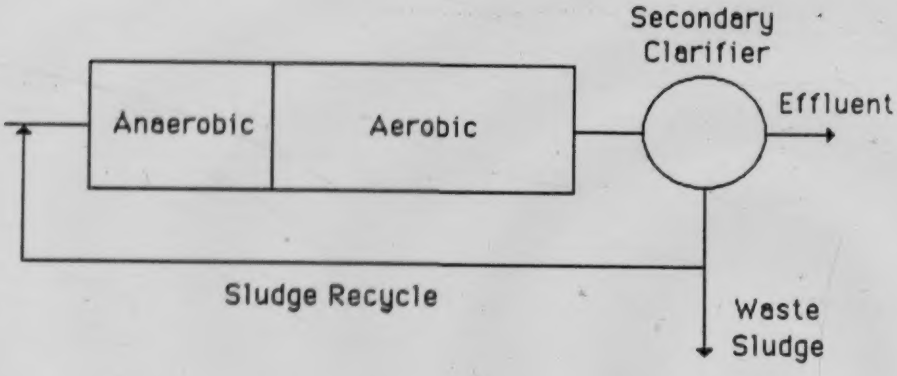

Secondary
Clarifier
Anaerobic
Aerobic
Effluent
Sludge Recycle
Waste
Sludge

Figure 2.8 The A/O Process for Phosphorus Removal only.

implimentation of the system.

## 3. EXPERIMENTAL DESIGN OF PILOT PLANT STUDY

In order to best quantify the effects of three common control parameters on the biological phosphorus removal process a statistically designed experiment was used in the pilot plant study. The procedure used was a $2^3$ factorial design experiment. A brief discussion of the factorial design process is given below.

### 3.1 FACTORIAL DESIGN

Most biological or chemical process yields are determined by the influence of process variables or factors. The factorial design procedure can be shown to give the best and most efficient estimate of the effects of any controllable factor on a process. In addition, modification of any factor effect due to variation in other factors may be measured (Davies, 1979).

A full factorial design experiment designed to test n factors will test all factor combinations at each of m levels. This is termed an $m^n$ factorial and will require m x n independent random trials or runs. From these trials the average effect on the process of varying any single factor, over the range studied, can be ascertained. Also the change in effect of a particular variable brought about by a change in a second variable can be measured. This is termed a two or 1 x 2 level interaction. Consideration of interaction levels is important since it is often found that the simultaneous modification of two factors, the independent modifications of which have been found advantageous to the process, does not always cause an additive improvement and may in fact cause a decrease in process yield.

The effect on the two level interaction of variation in a third variable may also be calculated. This is a three or 1 x 2 x 3 level interaction. In general 1 x 2 x ... x n interactions can be measured but it is usually found that interactions greater than the two level are not statistically significant to the process.

One consideration that limits the application of the full factorial design experiment is the rapid increase in the necessary number of trials, as the number of factors increases. For example, consideration of three factors at two levels requires $2^3$ or 8 trials. Adding three more factors brings the total number of trials to $2^6$ or 64. Therefore, it is important to establish as much information about the processes involved so that the number of factors and levels studied can be minimized with confidence.

In the biological phosphorus removal study each trial or run required the construction of a complete bench scale secondary wastewater treatment plant. With due consideration to the cost of this construction and the labour required for maintenance, it was decided that the investigation of three controllable factors at two levels was the most that could be achieved. This gave a $2^3$ factorial design. The three factors chosen were:

1. aerobic detention time

2. anaerobic detention time
3. sludge age

The choice and levels of these variables are discussed in a later section. The level combinations for each of the eight trials are shown in Table 3.1. Note that while three significant figures are shown in the values in Table 3.1 these are retained primarily for calculation purposes. The actual detention times could not be measured to this degree of accuracy. A completed example, showing the analysis involved, for a complete $2^3$ factorial design is given in Appendix IV.

More complete discussions of the factorial design concept and its applications are given by, for example, Box *et al.*, Hunter (1978), Davies (1979) and Montgomery (1984).

### Table 3.1 Variable Settings in Each Reactor

| Reactor Number | Aerobic Detention Time (hours) | Anaerobic Detention Time (hours) | Sludge Age (days) |
|---|---|---|---|
| 1 | 1.68 | 0.84 | 5 |
| 2 | 5.04 | 0.84 | 5 |
| 3 | 1.68 | 3.36 | 5 |
| 4 | 5.04 | 3.36 | 5 |
| 5 | 1.68 | 0.84 | 15 |
| 6 | 5.04 | 0.84 | 15 |
| 7 | 1.68 | 3.36 | 15 |
| 8 | 5.04 | 3.36 | 15 |
| 9 | 5.06 | 1.68 | 10 |
| 10 | 6.72 | 0 | 10 |

# 4. FORMULATION OF PILOT PLANT STUDY

## 4.1 CHOICE OF FACTORS IN THE PILOT PLANT STUDY

Many factors, both known and unknown, may affect the efficiency of the biological phosphorus removal process. Since the activated sludge process operates in a dynamic state it is important to know the effects and interactions on the process, of those few parameters which may be designed or controlled. If this knowledge is available it should be possible to present the best combination of factor settings to achieve good phosphorus removal.

Since it is currently believed that every biological phosphorus removal plant must have an anaerobic zone followed by an aerobic zone and since sizing criteria for these zones remain indefinite, two of the three factors chosen for the study were anaerobic zone hydraulic detention time and aerobic zone hydraulic detention time. The third factor chosen was the solids retention time (SRT) which is used as the controlling parameter in many activated sludge wastewater treatment plants.

### 4.1.1 THE ANAEROBIC ZONE HYDRAULIC DETENTION TIME AS A FACTOR IN THE BIOLOGICAL PHOSPHORUS REMOVAL PROCESS

Since researchers became aware of the necessity for an anaerobic zone in biological phosphorus removal plants (Levin, 1972; Barnard, 1974) the sizing and hence the detention time of the anaerobic reactor has, for the most part, been done on an empirical basis. In the PhoStrip process because the return sludge undergoes a separate anaerobic treatment in which virtually the only carbon source available is through endogenous respiration, the detention times in the anaerobic reactor tend to be long. In their original pilot plant Levin é (1972) used an anaerobic detention time of ten hours.Anaerobic detention times of up to thirty hours have been reported (Barnard, 1983a).

Barnard (1974) in the original Bardenpho system used a detention time of three hours in both the first and third reactors. Since both of these zones were termed anoxic and were designed for nitrogen removal these detention times were based on denitrification kinetics. Osborn and Nicholls (1978) suggested that an anaerobic detention time of two hours should be sufficient if nitrates were likely to be present. They also suggested that controlled substrate addition or complete denitrification in the anaerobic zone would allow this to be reduced to one hour. These values were based on a pilot plant of a modified Phoredox type. (These plant configurations are discussed in Chapter 2).

Malrou *et al.* (1984) in batch testing of sludge from a modified Phoredox pilot plant used anaerobic detention times of one hour, two hours and three hours. They found that while the magnitude of release increased with increasing detention time essentially complete uptake was achieved in all cases after one to one and a half hours aeration. Therefore over the range studied the anaerobic detention time did not appear to be significant. Gerber and Winter (1984) reported that increased phosphorus removal occurred with increased anaerobic detention times. In their experiments they used anaerobic detention times (based on influent flow, without return sludge) of six, twelve, eighteen and twenty-four hours.

Therefore in general there exists no rational or standard method by which to design the anaerobic zone. Since most of the cases cited in the literature involve the presence of an anoxic zone for denitrification, how these findings would apply to a plant designed for phosphorus removal alone is unclear. Furthermore, very little is known about how the relative sizings of the anaerobic and aerobic zones affect the process or whether there exists an optimal ratio by which to best achieve biological phosphorus removal. As a result of this it was decided to use anaerobic detention time as a factor in the design. A range of 0.84 to 3.36 hours, as low and high levels was used.

### 4.1.2 THE AEROBIC ZONE HYDRAULIC DETENTION TIME AS A FACTOR IN THE BIOLOGICAL PHOSPHORUS REMOVAL PROCESS

In addition to phosphorus, all biological phosphorus removal plants must remove carbonaceous substrate to an acceptable effluent level. Since both nitrification and carbonaceous substrate removal take place almost exclusively in the aeration reactor aerobic detention time has been designed, for the most part, on the basis of nitrification and COD removal kinetics. As a result there is generally no discernable difference between the aerobic detention times of biological phosphorus removal plants and equivalent type plants without biological phosphorus removing capabilities.

Therefore the effects of variation in aerobic detention time or the anaerobic/aerobic detention time ratio has received little address in the current literature. It was therefore decided to include the aerobic detention time as a variable in the experimental design. The range used was from 1.68 hours as a low level to 5.04 hours as a high level.

### 4.1.3 SLUDGE AGE AS A FACTOR IN THE BIOLOGICAL PHOSPHORUS REMOVAL PROCESS

The sludge age[also known as the Solids Retention Time (SRT) or the Mean Cell Residence Time (MCRT)] is commonly used as a control parameter in activated sludge wastewater treatment plants. How changes in this variable may be linked to phosphorus removal efficiency is not well documented.

In the design of nutrient removal plants in South Africa the SRT has usually been decided on nitrification considerations. Barnard (1974) quoted the following formula of Marais (1973) as appropriate:

$$SRT = 3.05(1.127)^{20-T} \quad T = \text{basin temperature, °C} \qquad [4.1]$$

Stall and Sherrard (1976) argued that for a particular net solids production a fixed quantity of phosphorus could be removed. They suggested that for a given cell and carbon source, phosphorus uptake would increase as the solids production increases. This in turn would result from a decrease in SRT. Thus it would seem as if lower rather than higher sludge ages should promote the maximum phosphorus uptake.

Mulbarger *et al.* (1971) found, in a full-scale study at the Manassas Sanitary District Treatment Plant, that maximum removal was achieved at a sludge age of approximately 3.6 days.

It must be noted, however, that at the time of these studies very little was known of the various other factors which influenced the process. For example, the necessity of an anaerobic stage was unknown. Whether the effects of sludge age as reported by these authors could be separated from other influences is unlikely.

In order to separate and measure the effect of SRT it was included as the third variable in the experimental design. A range considered typical for a conventional activated sludge plant was used. The high level was 15 days and the low level was 5 days.

## 4.2 EQUIPMENT AND MATERIALS

A full $2^3$ factorial design experiment, as outlined above, requires eight random trials to give the eight possible combinations of factor settings. In many cases this involves carrying out the trials in random order on the same equipment. With biological wastewater treatment systems this is almost impossible however, due to the long periods required by the bacterial mass to stabilize removal ability under changing environmental conditions. It therefore becomes necessary to replicate the equipment.

To facilitate the $2^3$ factorial design ten bench scale treatment plants were constructed. Eight of the model plants were used directly in the factorial design, one was run at conditions approaching those of the full-scale Gold Bar pilot study and one was run under completely aerobic conditions. Variable nominal hydraulic detention times in the range of 0.84 to 3.36 hours and 1.68 to 5.04 hours were possible in the anaerobic and aerobic zones, respectively. Mixing was provided in the aerobic zone by a compressed air/diffusion stone arrangement and in the anaerobic zone by top-mounted vertical shaft paddle motors. In each case the reactors were followed by a two hour nominal detention time clarifier.

Return sludge pumping of the settled sludge from the clarifier to the anaerobic zone was provided. The clarified effluent was decanted and removed from the system. The reactors and clarifiers were constructed from clear plexiglass. Settled municipal wastewater from the full scale primary clarifiers was pumped to a control storage container from which it was pumped to an elevated constant-head tank. This tank helped to ensure that the feed, to each reactor, remained constant. Flow control valves were also fitted to the feed lines. The reactors were initially seeded with return sludge from the section of the Gold Bar Wastewater Treatment Plant which had previously been modified to achieve biological phosphorus removal. A complete description of the equipment used in this study is given in Appendix I.

## 5. METHODS AND PROCEDURES

From start up of the bench scale project on August 13th, 1985 to the initiation of an intense monitoring and sampling period on October 7th, 1985, the phosphorus removal in the reactors was monitored. This eight week period allowed stabilization of the biomass to occur. Practice was obtained in the various sampling techniques and operational problems were also solved during this time. The sampling results of this stabilization period are presented in Appendix III.

On October 7th, 1985 an intense sampling period lasting ten days was initiated. During this period, various parameters supplemental to total and orthophosphate were measured. An initial influent sample was taken from the constant-head tank at 8:00 a.m. daily. This sample allowed estimation of the influent wastewater characteristics for the particular day. Two samples were taken after each of three, four, six and ten hours. Samples were taken from the extra two reactors after eight and ten hours, respectively. Thus a total of eleven samples were taken daily. In addition measurements through each cell of a different reactor were taken daily over the ten day period. The measurements through the reactor are referred to as profile measurements. The tests carried out on all the samples are described below. The analytical procedures are listed and referenced in Appendix 1. A listing of the days and dates of the intense sampling period is given in Table 5.1.

Table 5.1 Dates of Sampling Period

| Day | Date |
|---|---|
| 1 | Monday, October 7, 1985 |
| 2 | Tuesday, October 8, 1985 |
| 3 | Wednesday, October 9, 1985 |
| 4 | Thursday, October 10, 1985 |
| 5 | Friday, October 11, 1985 |
| 6 | Saturday, October 12, 1985 |
| 7 | Sunday, October 13, 1985 |
| 8 | Monday, October 14, 1985 |
| 9 | Tuesday, October 15, 1985 |
| 10 | Wednesday, October 16, 1985 |
| 11 | Thursday, October 17, 1985 |
| 12 | Friday, October 18, 1985 |
| 13 | Saturday, October 19, 1985 |
| 14 | Sunday, October 20, 1985 |
| 15 | Monday, October 21, 1985 |

## 5.1 BIOCHEMICAL OXYGEN DEMAND (BOD)

$BOD_5$ tests were used in order to record the carbonaceous substrate removal within each reactor.

Filtered and unfiltered $BOD_5$ determinations were made on all samples. Filtration consisted of vacuum filtration through a Whatman #2 GFC filter paper. For each sample two dilutions were used to ensure a measurable result. Three replicates were taken at each dilution.

## 5.2 CHEMICAL OXYGEN DEMAND (COD)

Filtered and unfiltered COD tests were also performed on all samples. Unfiltered COD acted also as a measurement of treatment in the reactors. GFC filtered samples acted as a measurement of rapidly absorbed and biodegradable COD. COD samples were taken from every reactor cell as part of the COD profile determination throughout each reactor.

## 5.3 ORTHOPHOSPHATE FORMS

Filtered and unfiltered orthophosphate was determined daily for the influent and effluent from all reactors. Filtration consisted of filtration through a Whatman #2 GFC filter paper followed by further filtration through a 0.45 µm Millipore filter paper.

Determinations were made both by the laboratory staff at Gold Bar Wastewater Treatment Plant and by the operators of the bench scale plant. Statistical t-tests showed that there ws no significant difference at the 99% level between the results obtained even though two different methods were utilized.

## 5.4 TOTAL PHOSPHORUS (TP)

Total phosphorus determinations were carried out by the laboratory staff of the Gold Bar Wastewater Treatment Plant, on a daily basis.

## 5.5 TOTAL SUSPENDED SOLIDS (TSS), VOLATILE SUSPENDED SOLIDS (VSS)

Total suspended solids measurements were made on the influent and effluent of each reactor on a daily basis. In addition, the TSS concentration in each cell was determined for reactor profile studies.

Volatile suspended solids measurements were also made on all of the above samples.

## 5.6 DISSOLVED OXYGEN (DO)

Dissolved oxygen measurements were taken in all reactor cells on a daily basis.

## 5.7 OXIDATION-REDUCTION POTENTIAL (ORP)

Oxidation-reduction potential measurements were taken in all reactor cells on a daily basis.

## 5.8 NITROGEN FORMS

Nitrate and nitrite nitrogen measurements were made on the influent and effluent of each reactor and on the mixed liquor of each anaerobic cell in every reactor. The anaerobic cell sampling did not follow a scheduled pattern but each cell was sampled at least once during the sampling period.

## 5.9 pH

Measurements of pH were taken in all reactor cells on a daily basis.

# 6. RESULTS AND DISCUSSION

## 6.1 ACHIEVEMENT OF PHOSPHATE - PHOSPHORUS REMOVAL

Phosphate-phosphorus removals, over the sampling period, for the reactors used in the experimental design are shown in Figures III.1 to III.8, Appendix III and in Table 6.1. Biological phosphorus removal was achieved to some degree in all eight reactors. The range of removal on any particular day varied considerably among the reactors. This was to be expected since the purpose of the factorial design is to examine the complete range of factor combinations, from the optimal to the worst.

A large degree of effluent phosphorus fluctuation within the individual reactors over the ten days was also observed. The reasons for this are unclear. Within reactors operating farthest from those conditions which analysis (shown later in this chapter) shows to be optimal poor phosphorus removal and fluctuating effluent quality due to poor-conditioning of the phosphorus removing bacteria was also to be expected. Examination of the effluent concentrations from those reactors (reactors four and eight) which normally achieved good phosphorus removal shows that on occasions large fluctuations in effluent phosphorus concentration occurred.

This can be seen readily from Figures 6.1 and 6.2. Such fluctuations in the reactors with the best performance give reason for concern since the bacteria in these reactors exhibit the highest storage capacity and consequently have the potential to release large quantities of phosphorus under conditions of stress.

On day nine of the sampling period high effluent phosphorus concentrations were noticed from all the reactors. It was believed that a condition of stress had occurred which caused the bacteria to release previously stored phosphorus to the effluent. This belief was reinforced by the effect on reactors eight and four, normally the best performing reactors. In both cases the effluent phosphate-phosphorus exceeded the influent concentration and by almost the same amount.

Recovery took place over the following three days with similar effluent concentrations from each of the two reactors. From analysis of the overall results (shown in a later section) reactor eight was considered to have the factor settings closest to the optimum, followed next by reactor four. Thus when the effluent quality began to decrease again for reactor four on day twelve reactor eight continued to achieve good removal. However by day fifteen both reactors were demonstrating poor removal. During this period varying levels of removal were achieved in the other reactors. It was impossible however to separate the fluctuation due to the factor settings from that due to any external influence.

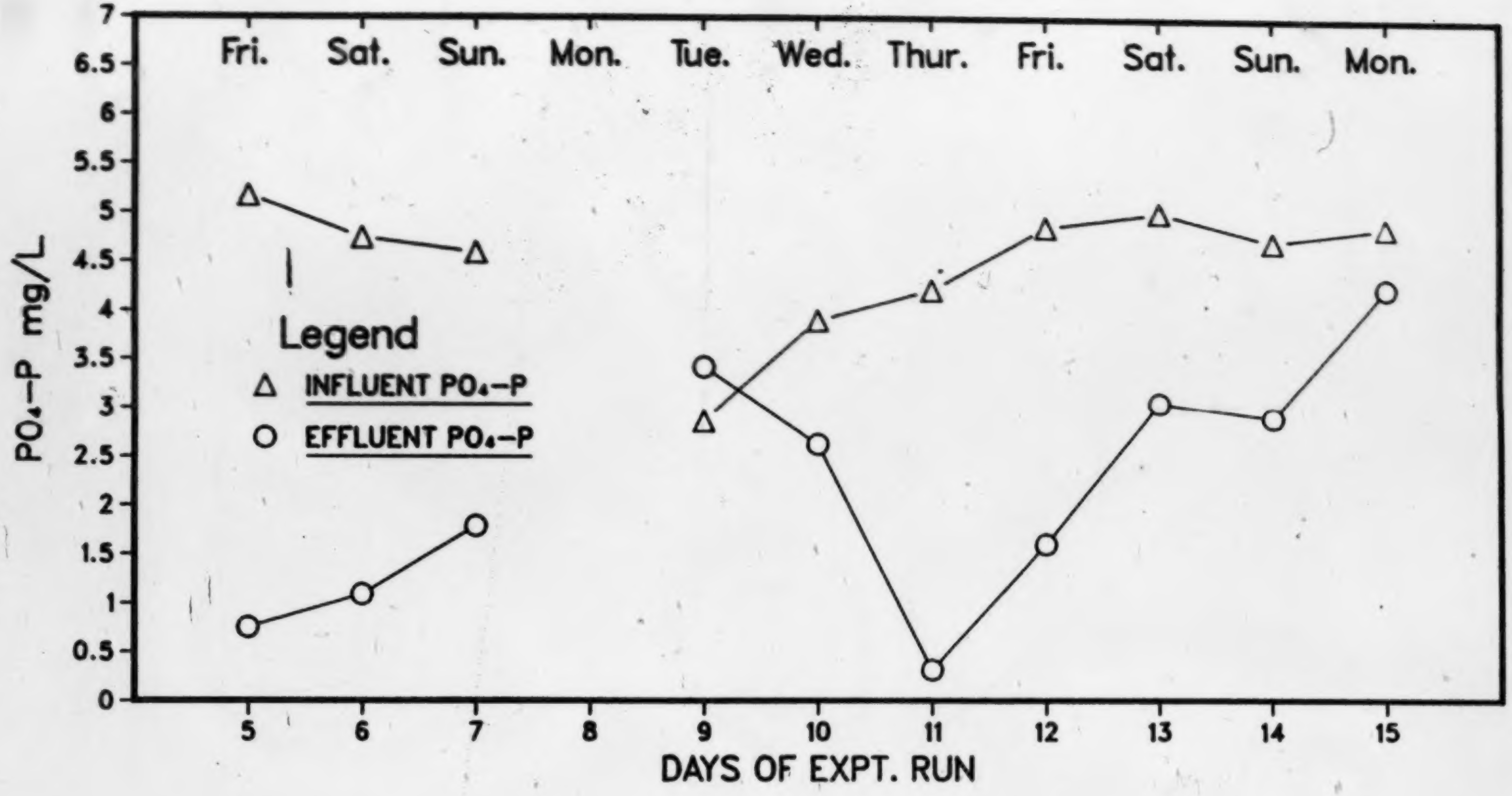


Figure 6.1 Influent and Effluent $PO_4$-P Concentrations for Reactor Number Four, Throughout the Sampling Period.

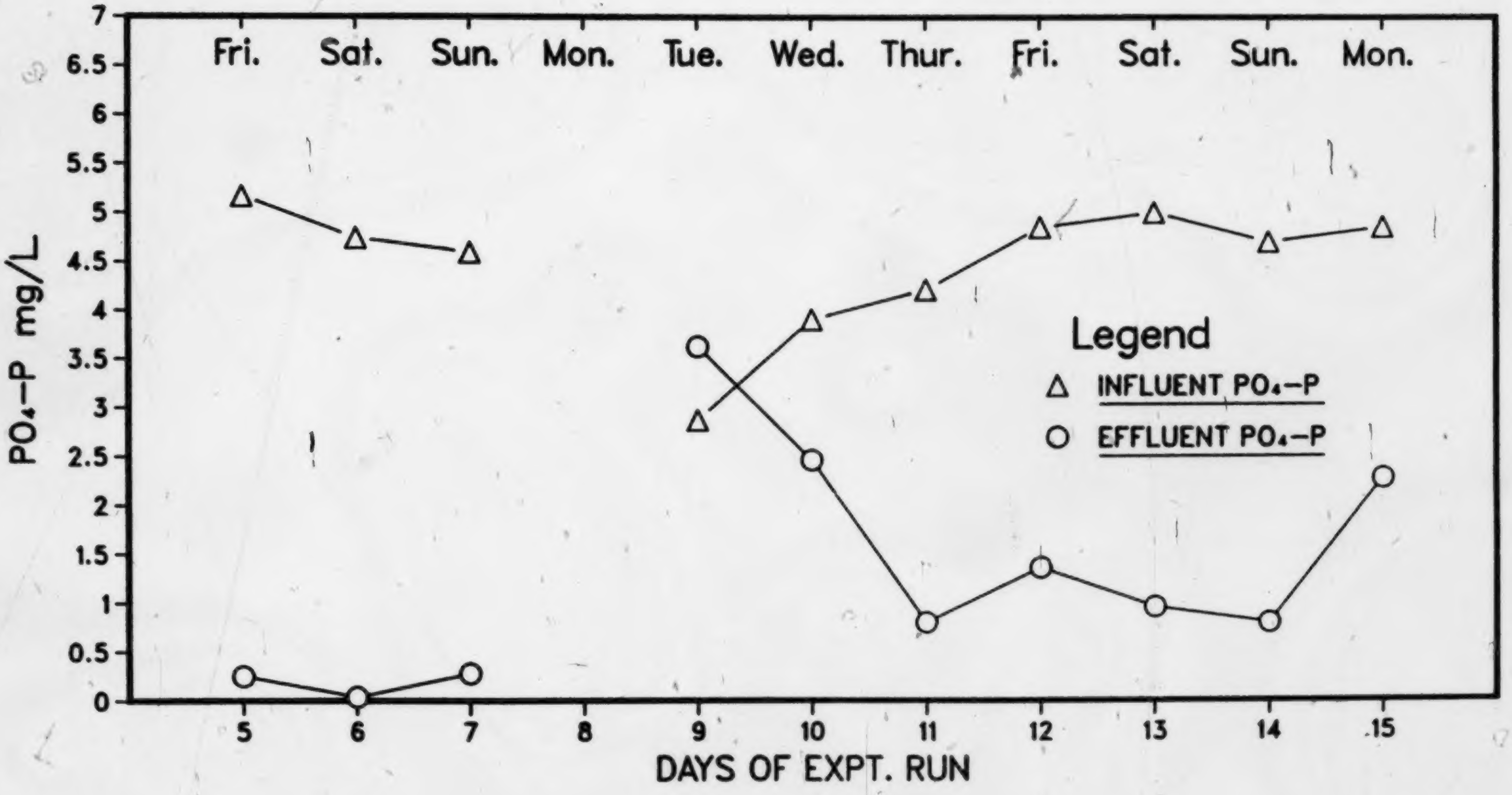


Figure 6.2 Influent and Effluent $PO_4$-P Concentrations for Reactor Number Eight, Throughout the Sampling Period.

Table 6.1 Influent and Effluent Orthophosphate-Phosphorus Concentrations for Each Reactor Throughout Sampling Period.

| Day | Influent $PO_4$-P (mg/L) | Effluent $PO_4$-P conc. (mg/L)<br>Reactor Number††<br>1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 5.17 | 1.29 | 2.25 | 2.98 | 0.75 | 0.56 | 2.55 | 1.25 | 0.25 | 0.42 | 2.38 |
| 6 | 4.74 | 0.81 | 2.55 | 3.45 | 1.09 | 2.00 | 2.82 | 3.60 | 0.04 | 0.33 | 2.68 |
| 7 | 4.59 | 1.31 | 4.66 | 4.13 | 1.79 | 0.30 | 4.87 | 3.30 | 0.28 | 1.47 | 0.28 |
| 8 | - | - | - | - | - | - | - | - | - | - | |
| 9 | 2.87 | 2.58 | 5.43 | 1.92 | 3.42 | 2.13 | 3.29 | 1.76 | 3.63 | 3.26 | 3.42 |
| 10 | 3.90 | 2.01 | 3.17 | 2.94 | 2.63 | 0.57 | 2.79 | 2.21 | 2.46 | 2.00 | 3.93 |
| 11 | 4.21 | 1.36 | 5.33 | 4.07 | 0.32 | 1.41 | 3.16 | 2.68 | 0.80 | 0.88 | 3.34 |
| 12 | 4.85 | 2.36 | 4.70 | 2.23 | 1.61 | 0.28 | 4.11 | 1.87 | 1.36 | - | 1.36 |
| 13 | 5.00 | 1.57 | 5.15 | 2.11 | 3.05 | 2.27 | 4.30 | 1.87 | 0.96 | - | 0.96 |
| 14 | 4.70 | 0.15 | 3.86 | 3.47 | 2.90 | 1.46 | 4.43 | 0.93 | 0.80 | - | 0.80 |
| 15 | 4.85 | 4.43 | 4.70 | 3.25 | 4.23 | 2.95 | 4.85 | 1.72 | 2.27 | - | 2.27 |

---

††See Table 3.1 for Variable Settings for each reactor.

Comparison with the performance of the full-scale pilot plant at Gold Bar Wastewater Treatment Plant showed a similar decrease in removal over the same period (Figure 6.3). Consultations with the staff at Gold Bar had revealed that postweekend reduction in effluent phosphorus quality was a regular occurrence. Originally it was suggested that reduced flows over the weekend would result in higher than normal nitrification in the aerobic section of the full scale plant, due to increased detention time. This in turn would be expected to elevate the the nitrate concentration in the return sludge to the anaerobic section. Thus the level of anaerobiosis would be reduced and the phosphorus release/uptake cycle adversely affected.

Strict flow control in the bench-scale pilot plants over the complete sampling period, showed that this suggestion failed to explain the observed effluent phosphorus fluctuations. Therefore it seemed that compositional variation in the influent wastewater was the most likely cause. It was noted that both the influent phosphorus and COD concentrations fell over the weekend. No significant correlation could be found between either influent phosphorus or influent phosphorus/COD ratio and the observed effluent phosphate-phosphorus concentration. Therefore it would seem as if some combination of unknown characteristics of the influent wastewater fluctuate causing a cyclical deterioration in the phosphorus removal capability of both large and small scale plants. It is

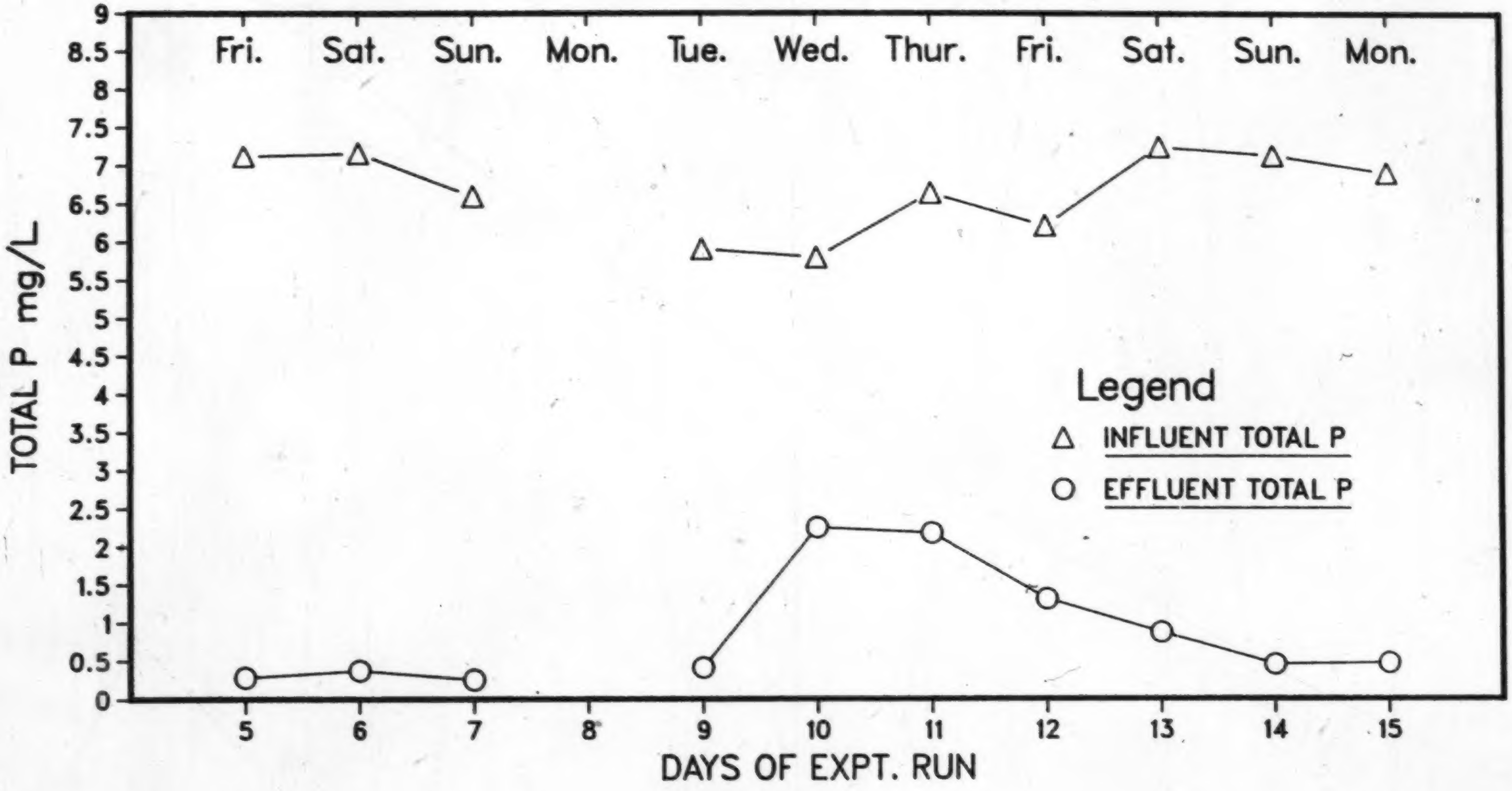


Figure 6.3 Influent and Effluent Total Phosphorus Concentrations for the Full-Scale Biological Phosphorus Removal Pilot Plant at the Gold Bar Wastewater Treatment Plant, Throughout the Sampling Period.

possible that the reduced COD allowed increased nitrification to occur in spite of a constant aeration time.

Further study in this area is therefore warranted especially with regard to characterization of the influent wastewater and its effects on phosphorus removal.

Table 6.2 Main Effects and Interactions for Phosphorus Removal, Throughout the Sampling Period.

| Day | Main Effects | | | Interactions | | | | Average |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 12 | 13 | 23 | 123 | |
| 5 | -0.070 | -0.035 | -0.665 | -1.545 | 0.565 | -0.450 | 0.050 | 1.485 |
| 6 | -0.840 | 0 | 0.140 | -2.120 | -0.530 | -0.590 | -0.070 | 2.045 |
| 7 | 0.640 | -0.410 | -0.785 | -3.320 | 0.135 | -0.385 | -0.475 | 3.580 |
| 8 | - | - | - | - | - | - | - | |
| 9 | 1.843 | -0.678 | 0.638 | 0.163 | -0.333 | 0.678 | 0.513 | 3.019 |
| 10 | 0.830 | 0.425 | -0.680 | -0.860 | 0.405 | 0.230 | -0.125 | 3.348 |
| 11 | 0.023 | -0.848 | -0.758 | -2.838 | -0.088 | 0.303 | 1.023 | 2.391 |
| 12 | 1.260 | -1.095 | -0.820 | -1.825 | 0.400 | 0.515 | -0.345 | 2.315 |
| 13 | 1.410 | -1.325 | -0.620 | -1.395 | -0.850 | -0.545 | -0.075 | 2.660 |
| 14 | 1.495 | -0.450 | -0.690 | -1.845 | -0.075 | -1.630 | 0.295 | 2.250 |
| 15 | 0.925 | -1.365 | -1.205 | -0.160 | 0.300 | -0.540 | -0.515 | 3.550 |

## 6.2 EFFECTS OF FACTOR SETTINGS ON BIOLOGICAL PHOSPHORUS REMOVAL

The calculated main effects and interactions for each of the ten days are shown in Table 6.2. Originally it was hoped to consider the results as coming from ten replicates of the same experiment. The day to day fluctuations discussed above made such a comparison invalid, however. These fluctuations did give an opportunity to study removal capacity under varying conditions reflective of those being met by the full scale plant. In order to test the significance, on the removal process, of the calculated effects and interactions Fisher's Analysis of Variance (ANOVA) technique was utilized. This statistical technique aids in differenciating between random variations in measured observations and variations truely caused by particular factor settings.

Since true replication of the experiment, in terms of duplicate reactors at the same settings, proved impossible due to financial and manpower considerations, the aerobic detention time x anaerobic detention time x sludge residence time interactions and various other interactions and effects were used to estimate the pure error variance. The choice of factors and interactions used was made following the Half-Normal Probability Technique of Daniel (1959). Examples of these plots are shown in Figure III.9 to Figure III.18.

The calculated effects and interactions for each trial (i.e. each reactor) showed no significant deviation from normality and therefore were valid for the application of the ANOVA technique. Analysis was carried out for each of the ten days' observations using the results of that day to estimate the pure error variance. This would account for or factor out analytical variation contributing to the overall between-treatment variance. Then each days' results were further analysed using the ten 1x2x3 interactions as a pooled estimate of error variance. The results of day eleven were omitted since the 1x2x3 interaction for this day was excessively large. Agreement between these two analyses would serve to reinforce the analytical conclusions. The ANOVA tables for the analysis are shown in Table 6.3 and Table 6.4. Table 6.3 shows the number of days during the sampling period when a particular effect or interaction reached or exceeded a chosen level of significance, using the same-day estimate of error variance. Table 6.4 shows the same data using the pooled estimate of error variance.

Table 6.3 Summary of Significance Levels reached by Main Effects and Interactions for $PO_4$-P Removal Using Same Day Estimate of Error Variance. (Day 11 excluded)

| Effect | Maximum Significance Level Reached (Number of Days) | | | Total Number of Days That The 90% Significance Level was Reached or Exceeded |
|---|---|---|---|---|
| | 90% | 95% | 99% | |
| 1 | 5 | 2 | 0 | 7 |
| 2 | 3 | 1 | 0 | 4 |
| 3 | 1 | 2 | 0 | 3 |
| 1x2 | 2 | 2 | 3 | 7 |
| 1x3 | 1 | 0 | 0 | 1 |
| 2x3 | 1 | 1 | 0 | 2 |

Table 6.4 Summary of Significance Levels reached by Main Effects and Interactions for $PO_4$-P Removal Using 1x2x3 Interactions as a Pooled Estimate of Error Variance. (Day 11 excluded)

| Effect | Maximum Significance Level Reached (Number of Days) | | | Total Number of Days That The 90% Significance Level was Reached or Exceeded |
|---|---|---|---|---|
| | 90% | 95% | 99% | |
| 1 | 1 | 3 | 4 | 8 |
| 2 | 1 | 0 | 3 | 4 |
| 3 | 5 | 2 | 1 | 8 |
| 1x2 | 0 | 1 | 6 | 7 |
| 1x3 | 0 | 1 | 0 | 1 |
| 2x3 | 1 | 0 | 1 | 2 |

## 6.3 INTERPRETATION OF ANALYTICAL RESULTS

From both Table 6.3 and Table 6.4 it can be seen that over the sampling period the aerobic detention time x anaerobic detention time interaction was most often significant and at high significance levels. This interaction will be referred to as the 1x2 interaction. Therefore the 1x2 interaction affected the process more often than any other effect or interaction.

The aerobic detention time main effect (1 main effect) was also frequently significant at high significance levels and therefore must also be considered important to the process. The sludge age main effect also showed significance but at a lower (90%) significance level.

The meaning of these results may be best realized by considering in detail the results of an individual day. As an example the discussion of the results on day 12, one of the majority of days on which the effects and interactions noted above were significant, will be considered.

For day 12 the aerobic detention time main effect (hereafter referred to as the 1 main effect) was calculated as 1.26. This indicated that, on average, the effluent phosphate-phosphorus concentration resulting from reactors with high aerobic detention times was 1.26 mg/L greater than that resulting from reactors with low aerobic detention times. These high and low detention times were nominally 5.04 and 1.68 hours, respectively. The aerobic detention time x anaerobic detention time or 1x2 interaction which was calculated as -1.825 had an even higher significance level than the 1 main effect.

Therefore the 1 main effect differed between the high and low settings of anaerobic detention time by an amount equal to 2 x -1.825 or -3.65 mgP/L. This 1x2 interaction equals half the difference between the 1 main effect at the high and low settings of 2. Consider the calculations by which these values are derived. The reader is at this stage referred to the example factorial analysis in Appendix IV. The 1 main effect (1 M.E.) is calculated below.

$$1 \text{ M.E.} = \tfrac{1}{4}[(4.7 - 2.36) + (4.1 - 0.28) + (1.61 - 2.23) + (1.36 - 1.87)] = 1.26$$

Two of the four contrasts contributing to the 1 main effect were obtained by increasing the aerobic detention time while the anaerobic detention time was at a high level and the other two contrasts were obtained while the anaerobic detention time was at a low level. Consider the 1 main effect at the high and low levels of 2, individually.

At high 2 (3.36 hours):

$$1 \text{ M.E.} = \tfrac{1}{2}[(1.61 - 2.23) + (1.36 - 1.87)] = -0.565$$

At low 2 (0.84 hours):

$$1 \text{ M.E.} = \tfrac{1}{2}[(4.70 - 2.36) + (4.10 - 0.28)] = 3.080$$

The interaction effect is clearly shown. A low anaerobic detention time combined with a high aerobic detention time was detrimental to the removal process whereas a high anaerobic detention time combined with a high aerobic detention time increased the removal. Similar calculation shows that the high anaerobic/low aerobic detention time is also detrimental to the removal process. Thus the aerobic and anaerobic detention times must both be high or must both be low. Since increasing the anaerobic detention time produces, on average, a decrease of 1.095 mgP/L, i.e. the 2 main effect equals -1.095, a high, high combination is indicated.

In considering the setting for the third variable, sludge age, we can see that neither the 1x3 or 2x3 interactions are significant. In fact these interactions were rarely significant at high levels at any stage of the sampling period. The optimal setting of sludge age is therefore indicated by the 3 main effect alone. The analysis of variance shows the 3 main effect to be significant at the 90% level. While this is lower than the 1x2 interaction or the 1 main effect a choice of sludge age which acknowledges the negativity of the 3 main effect would be appropriate.

The above analysis suggests the +, +, + or high factor settings combination as the best combination, over the range studied, for orthophosphate removal. This combination was used in reactor number eight. Due to the lower significance of sludge age to the process, the +, +, - combination would also be expected to achieve good removal. This was the combination of reactor number four. Reactors number two and three would be expected to perform badly due to the 1x2 interaction.

The analysis carried out above is based on the results of one day. The results on this day are indicative of the trend in the data since on six of the seven days that the 1 main effect was significant it had a positive value, as above. On seven of the seven days that the 1x2 interaction was significant it had a negative value, as above, and on six of the six days that the 3 main effect was significant it too had a negative value, as above.

Therefore, while the data obtained and the results calculated showed some variation, the conclusions drawn from the analysis were consistant for almost 80% of the sampling period.

It is interesting to note the simultaneous variation in $PO_4$-P effluent concentration and the magnitude of the 1x2 interaction in reactor number eight. This is demonstrated in Figure 6.4. The 1x2 interaction appears smallest on days when high effluent $PO_4$-P was observed. In fact the change in the interaction magnitude seems to parallel the variation in effluent phosphorus concentration, over the ten day period. Thus the 1x2 interaction effect appears to be modified by variation in wastewater characteristics in a manner similar to that discussed above for effluent $PO_4$-P concentrations.

## 6.4 EFFECT OF FACTOR SETTINGS ON FILTERED COD REMOVAL

Influent and effluent COD concentrations were determined for all reactors during the sampling period. This data is listed in Appendix III and Table 6.5 and is shown graphically in Figure III.19 to Figure III.28, also in Appendix III. Since biological phosphorus removal plants are also expected to substantially reduce influent COD levels it was considered important to identify how the optimal factor settings for phosphorus removal might affect carbonaceous substrate removal.

An analysis of variance similar to that discussed above for phosphorus removal was carried out. A pooled estimate of the error variance was obtained from nine of the ten 1x2x3 interactions. The 1x2x3 interaction of day 11 was neglected since it was considered abnormally high. The ten days examined for COD removal were day 1 to day 11. No measurements were taken on day 8 (Monday, October 14, 1985) which was a public holiday. The ten days examined for phosphorus removal were day 5 to day 15. The reason for this disparity is described in Appendix II.

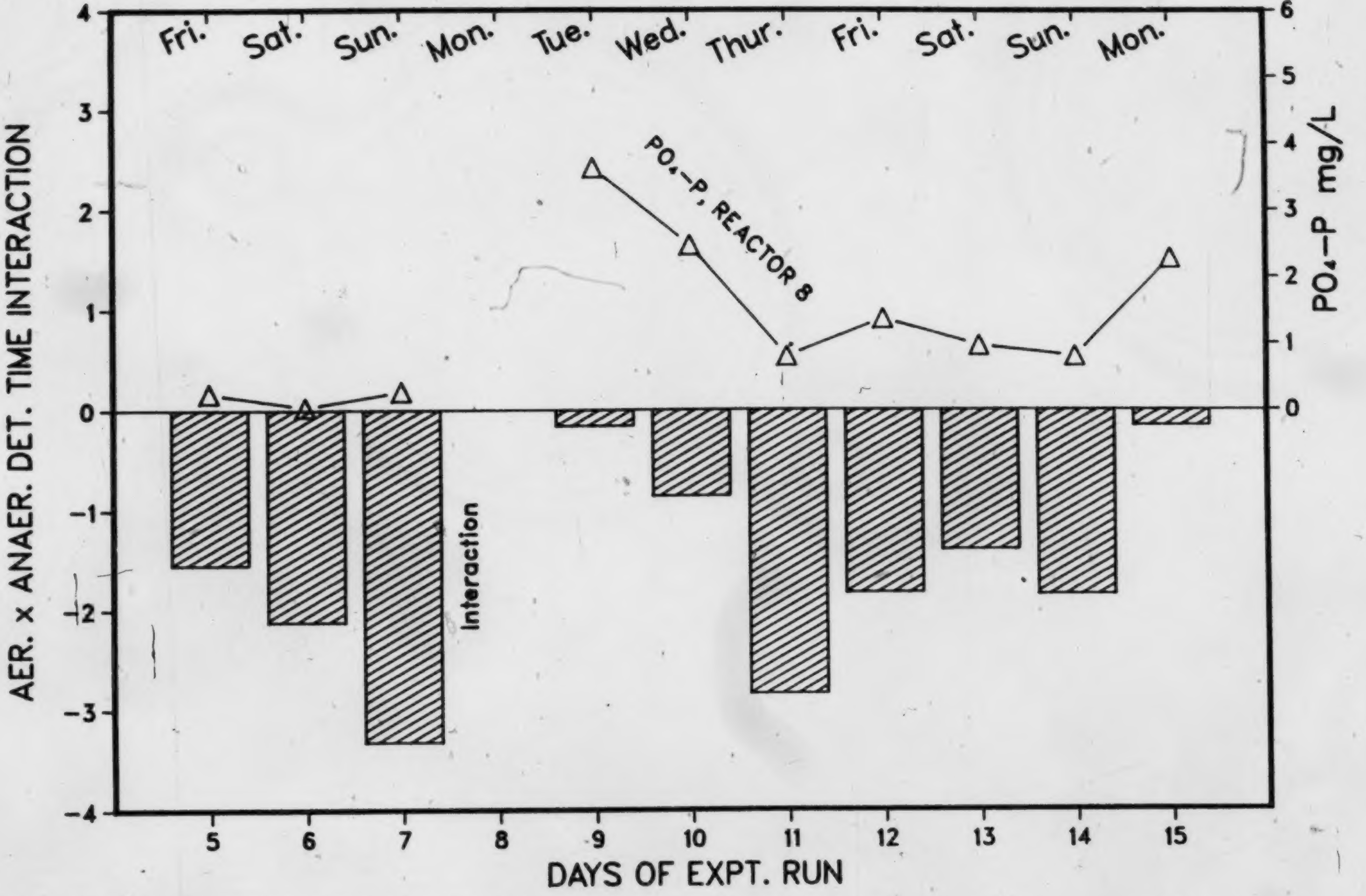


Figure 6.4 Comparison of the Variation in the 1x2 Interaction with the Variation in Effluent $PO_4$-P Concentration from Reactor Number Eight, Throughout the Sampling Period.

Table 6.5 Influent and Effluent Filtered COD Concentrations for Each Reactor Throughout Sampling Period.

| Day | Influent COD (mg/L) | Effluent COD conc. (mg/L) Reactor Number 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 134 | 47 | 38 | 48 | 69 | 55 | 45 | 77 | 76 | 76 | 63 |
| 2 | 214 | 78 | 49 | 72 | 43 | 90 | 42 | 63 | 45 | 45 | 52 |
| 3 | 179 | 57 | 40 | 39 | 38 | 56 | 40 | 51 | 51 | 44 | 40 |
| 4 | 173 | 55 | 35 | 54 | 43 | 66 | 23 | 50 | 43 | 43 | 43 |
| 5 | 226 | 47 | 3 | 58 | 30 | 51 | 19 | 58 | 39 | 31 | 28 |
| 6 | 154 | 47 | 46 | 47 | 59 | 71 | 55 | 47 | 39 | 95 | 56 |
| 7 | 123 | 56 | 41 | 66 | 52 | 56 | 18 | 57 | 40 | 40 | 40 |
| 8 | - | - | - | - | - | - |  | - | - | - | - |
| 9 | 77 | 27 | 38 | 52 | 41 | 33 | 33 | 46 | 37 | 37 | 28 |
| 10 | 161 | 50 | 38 | 64 | 40 | 55 | 39 | 45 | 32 | 30 | 33 |
| 11 | 157 | 34 | 54 | 93 | 32 | 36 | 33 | 38 | 26 | 25 | 25 |

The effluent filtered COD concentration as a percentage of the influent filtered COD concentration was considered in the COD analysis. Using this form of removal measurement rather than percentage removal meant that a negative main effect indicated an improvement in effluent quality in a manner similar to the phosphorus removal analysis. In fact the value of effects and interactions calculated by this method are numerically equal to those calculated using percentage removal and differ only in sign.

A summary of the significance levels of each factor on COD removal, over the sampling period, is shown in Table 6.6. The most noteworthy result is the frequent high significance of the aerobic detention time main effect (the 1 main effect). A significance level of 99% was achieved on five of the ten days of the sampling period. A 95% significance level was reached on one other day. The 1 main effect had a negative value on all six of these days. Since the 1x2 or 1x3 interactions did not achieve the same consistent high levels of significance this implies that, on average, increasing the aerobic nominal detention time from two to six hours resulted in increased COD removal. This is not an unexpected conclusion.

The analysis shows that the factor level for aerobic detention time chosen on the basis of phosphorus removal will also be advantageous for COD removal. The anaerobic detention time main effect was also significant at or in excess of the 95% level on five of the ten days. The values for this effect were positive on four of these days. Thus an increase in anaerobic nominal detention time is, on average, associated with reduced COD removal. Since the anaerobic bacteria may not be as efficient in COD removal as the aerobes this conclusion is reasonable.

On this basis choosing a high level of anaerobic detention time to promote phosphorus removal may cause some deterioration in effluent COD quality. The 1x2 interaction was also significant but at a lower level. This interaction was positive on most days further indicating the possible adverse effect of a high anaerobic detention time. Thus it would seem that a high, low or +, - combination of aerobic/anaerobic detention time would be optimal, over the range studied.

Table 6.6 Summary of Significance Levels reached by Main Effects and Interactions for Filtered COD Removal Using 1x2x3 Interactions as a Pooled Estimate of Error Variance (Day 11 excluded)

| Effect | Maximum Significance Level Reached (Number of Days) | | | Total Number of Days That The 90% Significance Level was Reached or Exceeded |
|---|---|---|---|---|
| | 90% | 95% | 99% | |
| 1 | 0 | 1 | 5 | 6 |
| 2 | 0 | 3 | 2 | 5 |
| 3 | 0 | 1 | 2 | 3 |
| 1x2 | 0 | 3 | 2 | 5 |
| 1x3 | 1 | 0 | 0 | 1 |
| 2x3 | 0 | 2 | 0 | 2 |

## 6.5 EFFECT OF FACTOR SETTINGS ON FILTERED BOD REMOVAL

Influent and effluent five day biochemical oxygen demand ($BOD_5$) concentrations were determined for each reactor on each day of the sampling period. This data is listed in Appendix III. An analysis of variance was also carried out on this data. The effluent filtered BOD as a percentage of the influent filtered BOD was used as the variable form in this case also. The 1x2x3 interactions for all days provided an estimate of error variance.

A summary listing of the significance levels reached by each of the parameters is shown in Table 6.7. Overall the analysis of variance showed that the data did not show any useful trends. The 99% confidence level was exceeded once only, by the aerobic detention time main effect and the anaerobic detention time main effect. On other occasions no effect seemed significant.

It is believed that these results may be due more to the lack of precision inherent in the BOD test than to an apparent lack of effect from all variable changes. The BOD results were then rejected in favour of those conclusions which could be drawn from the COD analyses.

**Table 6.7 Summary of Significance Levels reached by Main Effects and Interactions for Filtered BOD Removal Using 1x2x3 Interactions as a Pooled Estimate of Error Variance.**

| Effect | Maximum Significance Level Reached (Number of Days) |  |  | Total Number of Days That The 90% Significance Level was Reached or Exceeded |
|---|---|---|---|---|
|  | 90% | 95% | 99% |  |
| 1 | 2 | 2 | 1 | 5 |
| 2 | 0 | 0 | 1 | 1 |
| 3 | 1 | 0 | 0 | 1 |
| 1x2 | 0 | 0 | 0 | 0 |
| 1x3 | 0 | 1 | 0 | 1 |
| 2x3 | 0 | 0 | 0 | 0 |

## 6.6 COMPARISON OF EFFLUENT NITRATE-NITROGEN WITH EFFLUENT PHOSPHATE-PHOSPHORUS

During the sampling period analysis of the mixed liquor within the anaerobic cells failed to detect the presence of nitrate-nitrogen. While recognising that denitrification had occurred in the clarification stage it was decided to compare the effluent nitrate-nitrogen concentrations with the effluent phosphate-phosphorus concentrations. High nitrate-nitrogen concentrations in the return sludge might explain reduced phosphorus uptake ability.

Plots of effluent nitrate-nitrogen concentrations versus effluent phosphate-phosphorus concentrations are shown in Figures III.57 to III.64 . Only in reactors two and six did there seem to be a correlation between effluent nitrate-nitrogen and effluent phosphate-phosphorus. Except for reactors four and eight the effluent nitrate-nitrogen concentrations were uniformly low. While the nitrate values for reactors four and eight were high this did not seem to affect the phosphorus uptake in these reactors. Therefore it does not appear as if nitrification can provide an explanation for the fluctuation in phosphorus uptake in this study.

## 6.7 REACTOR PROFILE ANALYSIS

During the sampling period simultaneous cell by cell analyses of the mixed liquor for various characteristic parameters were carried out for each reactor. These parameters included orthophosphate, oxidation-reduction potential, filtered COD and volatile suspended solids. Through these analyses it was hoped that any trends through the reactors would become apparent and also that information regarding the function of location within the reactor on these parameter values could be obtained.

In particular the extent of the orthophosphate release-uptake cycle indicative of the presence of phosphorus removing microorganisms, as reported in the literature could be investigated. The oxidation-reduction potential (ORP) was also measured as a test of findings in the literature suggesting an inverse correlation between ORP and orthophosphate concentration.

The results of these analyses will be discussed individually.

### 6.7.1 FILTERED COD PROFILES

The profiles through the reactors for filtered COD are shown in Figures III.29 to III.38. While soluble COD removal varied between reactors, in almost all cases the major portion of that removal which did take place was seen to occur within the first hour. In all cases this was within the anaerobic zone. Thus it can be seen that a cyclical exchange between anaerobic and aerobic conditions does not appear to adversely affect the bacteria responsible for filtered COD uptake. The anaerobic bacteria within the system appear capable of withstanding prolonged exposure to an aerobic environment while the aerobic phosphorus removers are not affected by anaerobic conditions.

Furthermore the coupling of COD uptake with high phosphorus release, particularly in reactors four and eight is demonstrated. The orthophosphate profile through each particular reactor is reproduced on the COD profile to allow comparison. Overall the results obtained conform well to those reported in the literature. Note that a dashed line on the COD plots is used to indicate points where there is suspicion that analytical error or incomplete mixing caused an uncharacteristically high value.

### 6.7.2 ORTHOPHOSPHATE-PHOSPHORUS PROFILES

Profiles of the orthophosphate-phosphorus concentrations throughout the reactors are not shown separately but are presented in conjunction with the other measured profile parameters, principally for comparison purposes. A release-uptake cycle was established to a certain degree in all reactors having an anaerobic stage. In agreement with the literature a greater degree of removal was observed in reactors which demonstrated the highest phosphorus release within the anaerobic zone. This finding remained consistent over the sampling period since these reactors were the best performers as established in the analysis discussed in Section 6.2.

Similarly the reactors with mixed high and low levels of anaerobic and aerobic detention times did not achieve the required level of release or uptake, particularly reactors three, six and seven. While reactor number two did achieve a reasonable release level the following uptake was not large enough to provide good overall removal.

### 6.7.3 OXIDATION-REDUCTION POTENTIAL

Oxidation-Reduction potential may be considered a measure of the oxidizing ability of the medium. From the results obtained over the sampling period, shown in Figures III.39 to III.46, it is apparent that a high degree of phosphorus release did not occur unless highly negative ORP conditions were present. Upon entry into the aerobic zone the ORP became positive and a certain degree of phosphorus uptake was noted in all cases.

While the inverse relationship between ORP and phosphorus concentration was a trend in all cases it was impossible to consider this as a predictive tool. No consistent indication of a minimum required ORP necessary for a high degree of removal could be ascertained. This is demonstrated by comparison between reactor number three (Figure 6.5) and reactor number four (Figure 6.6). In the former case an ORP of approximately -300mV in the first three cells was accompanied by an orthophosphate-phosphorus concentration of only 6 mg/L. In reactor number four however an ORP of only -180mV was accompanied by an orthophosphate-phosphorus concentration of approximately 10 mg/L.

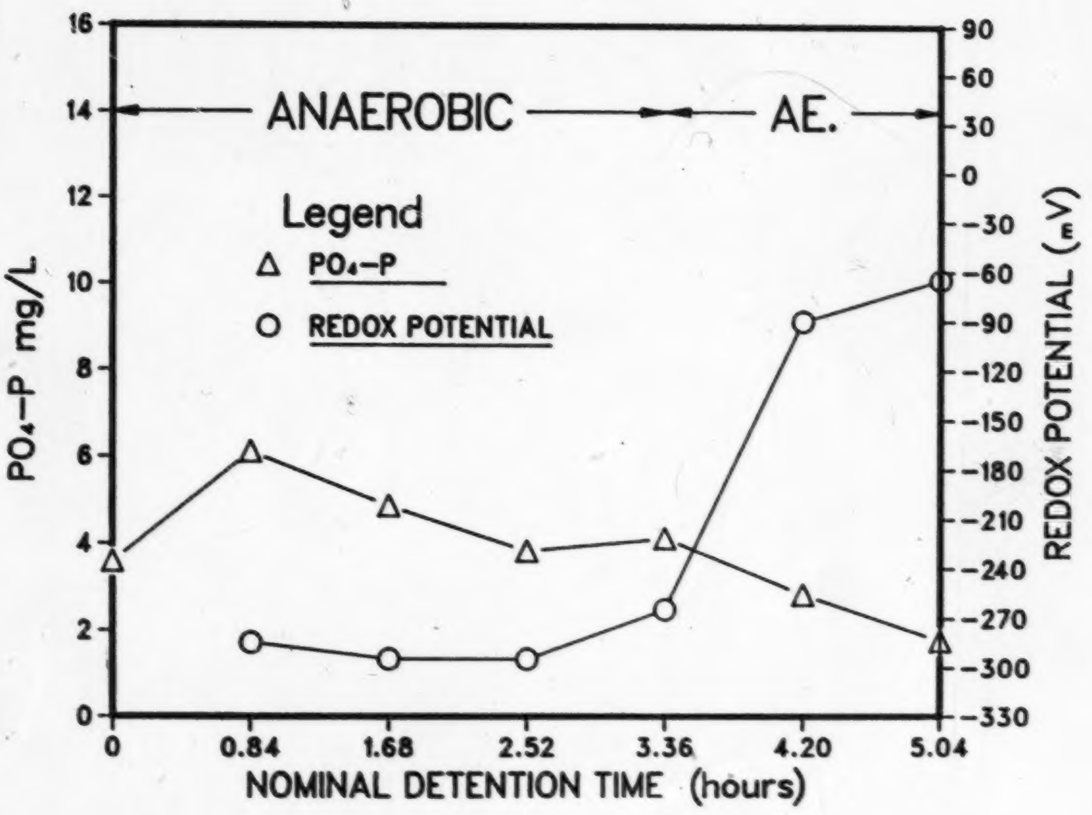


Figure 6.5 Profile of Redox Potential and $PO_4$-P Concentration Through Reactor Number Three.

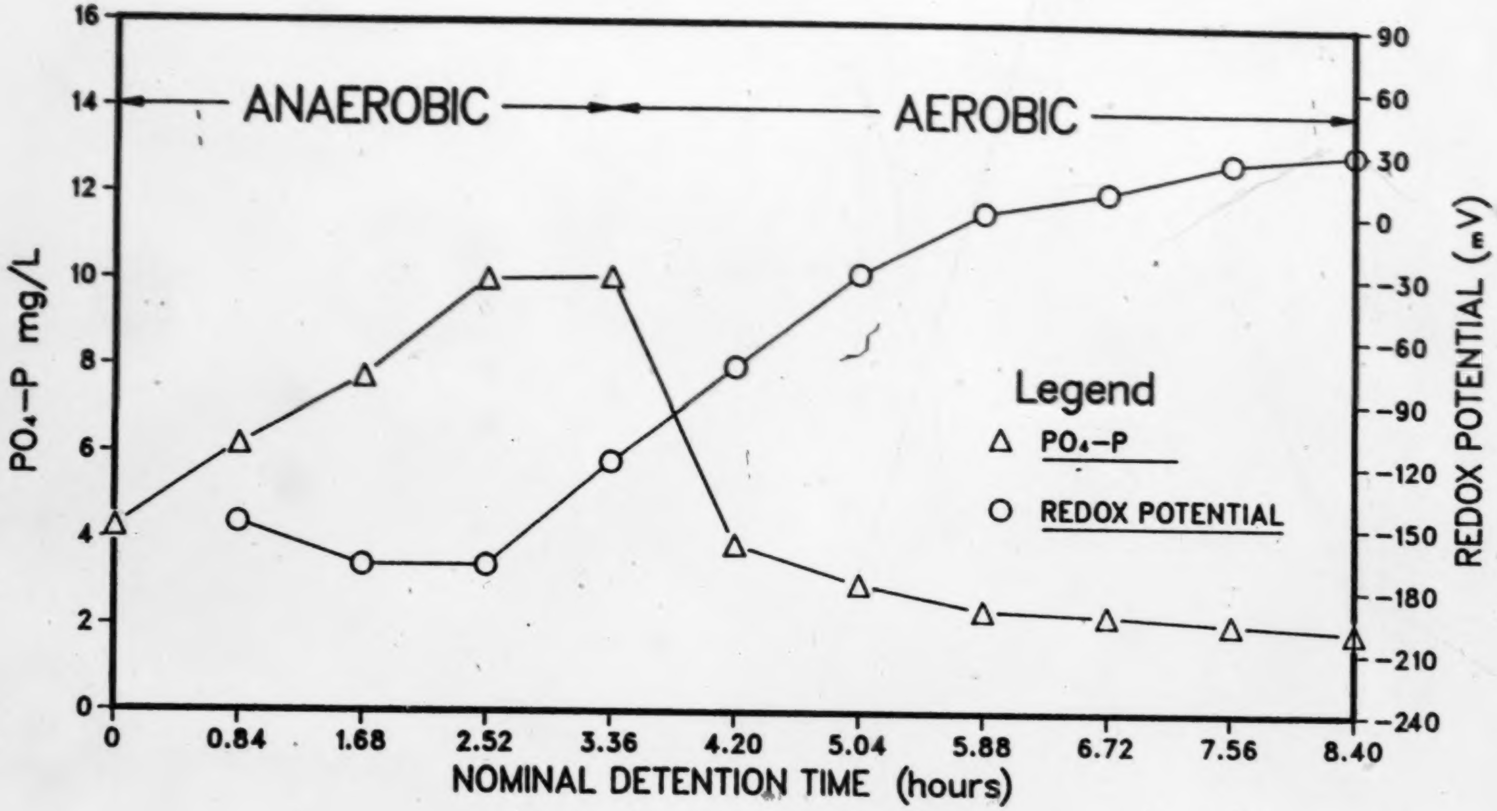


Figure 6.6 Profile of Redox Potential and $PO_4$-P Concentration Through Reactor Number Four.

Therefore an useful relationship is impossible to establish. It does seem however from the results obtained that the necessary release could not be expected under positive ORP conditions. This result is consistant with the literature. Note that due to time restrictions it was not possible to measure an ORP profile for reactor number seven.

### 6.7.4 VOLATILE SUSPENDED SOLIDS PROFILE

Profile concentrations of volatile suspended solids (VSS) through the reactors are shown in Figures III.47 to III.56. Orthophosphate-phosphorus concentrations are again reproduced for comparison purposes. Some fluctuations can be seen over the reactor length. These are most likely due to incomplete mixing and the plug-flow nature of several complete-mix stirred tank reactors (CSTR).

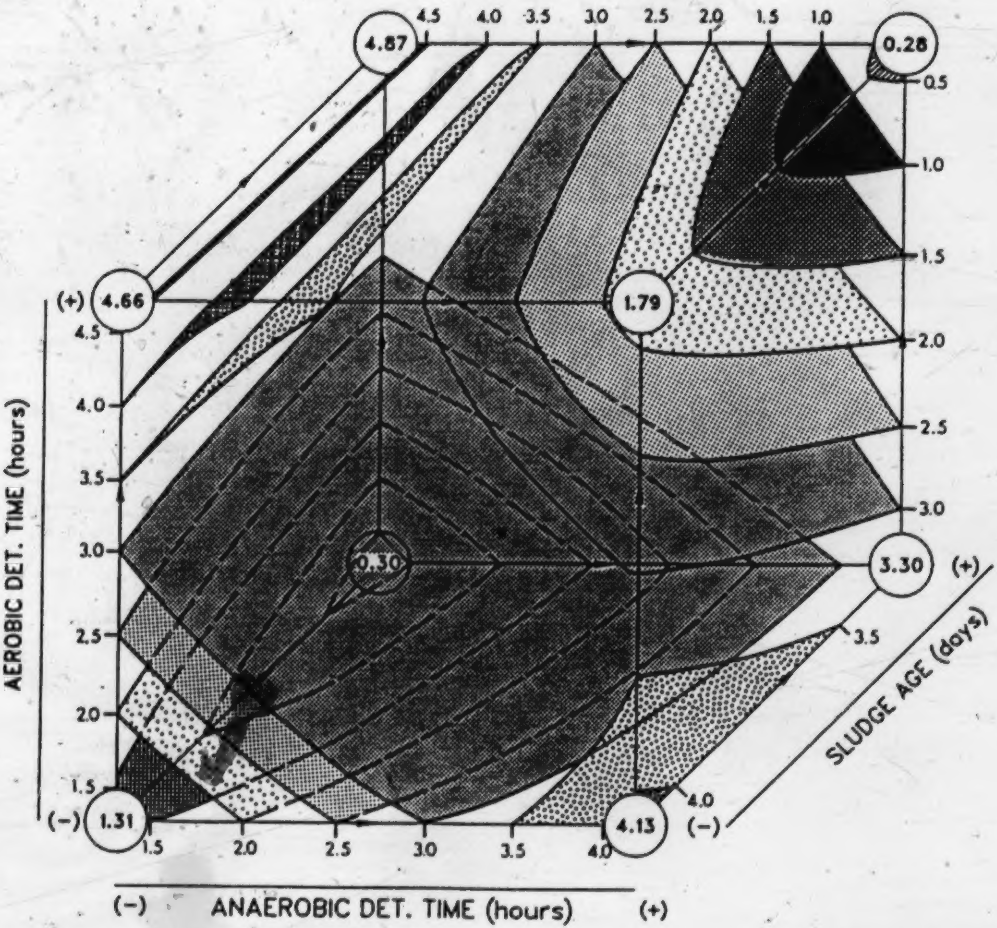
An overall trend towards VSS increase within the reactor did occur. This is probably indicative of a bacterial increase within the reactor which would be expected in a reactor operating under favourable conditions. No apparent inter-relationship between VSS concentration and orthophosphate-phosphorus under normal conditions was discernable though drastic losses of the biomass would undoubtedly affect the phosphorus removal performance of any reactor.

## 6.8 INFERENCES FROM THE EXPERIMENTAL ANALYSIS

Analysis of the data gained gave a good insight into the importance of the factors investigated and particularly the level of interaction between them. As a further step, the formation of a predictive model was attempted. From the experimental design utilized, if the phenomenon varies as a linear function of the variables investigated the best fitting model will be obtained. Varied attempts to fit the biological phosphorus removal data failed to produce a consistent or valid linear predictive model.

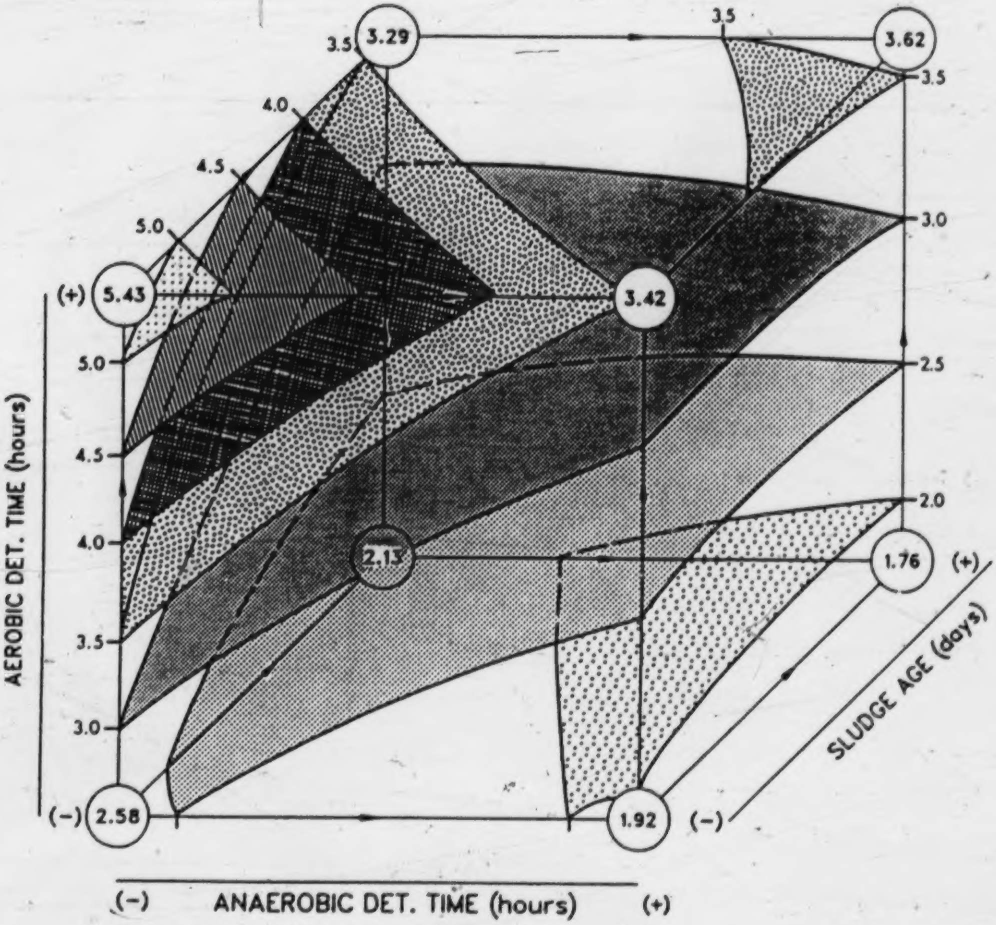
It may therefore be concluded that the biological phosphorus removal process is related in a complex manner to many variables. Those variables which were investigated been shown to have an important and clearly discernable effect but are incapable of totally describing the phenomenon. The cause of the cyclical deterioration in effluent quality, for example, must be considered external to the variables studied.

To show the variation in removal with time and other unknown variables an estimated response surface was plotted over the sampling period. This is shown in Figures 6.7 to 6.16. From these figures it is evident that the removal process is definitely non-linear in the parameters studied and almost certainly is affected by other unknown variables. It can also be seen that the response surface appears to be in a state of constant flux thus making prediction impossible. Note that the + and - signs refer to the high and low levels of each variable (see Section 3). The encircled numbers are the average of all reactor effluent phosphate-phosphorus concentrations obtained at the factor combination shown, on the particular day noted. The numbers shown on the edge of the cube are expected effluent phosphate-phosphorus concentrations for any particular combination of factors.



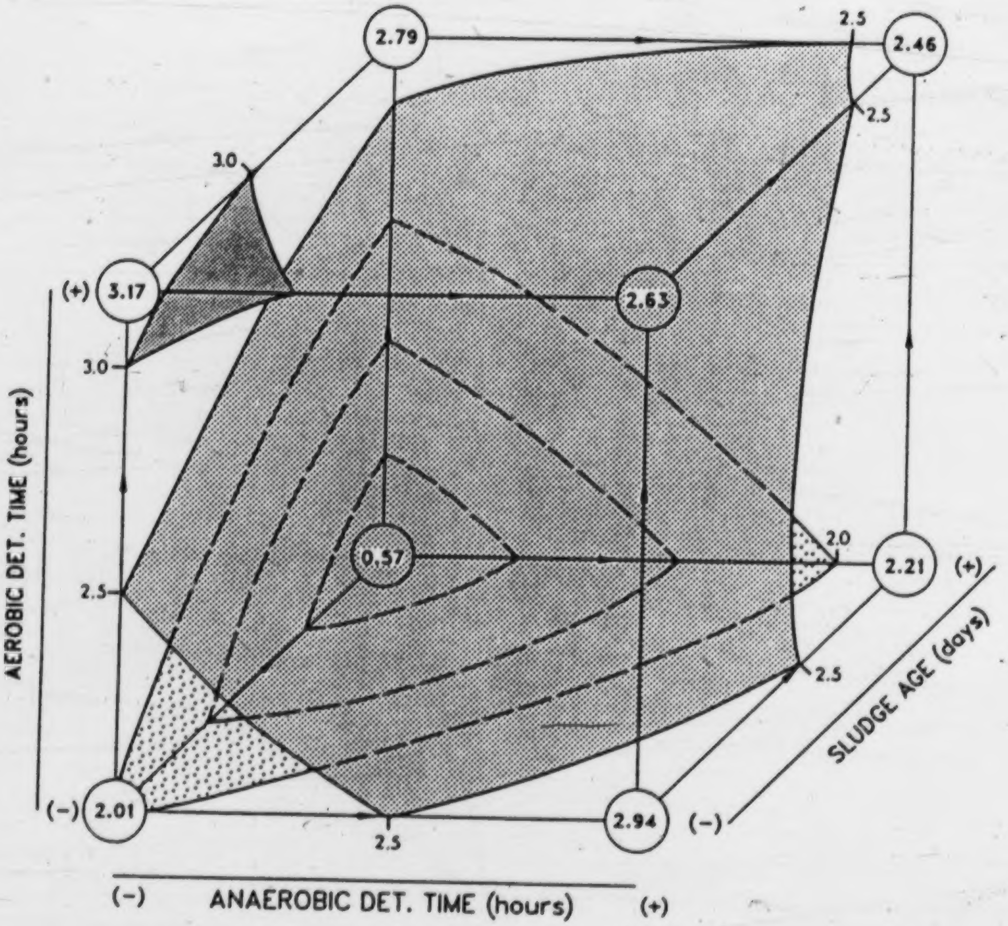
Note: See page 112 for a full explanation of this figure.

Figure 6.7 Estimated Response Surface for $PO_4$-P Removal Factorial Design, (Day 5).



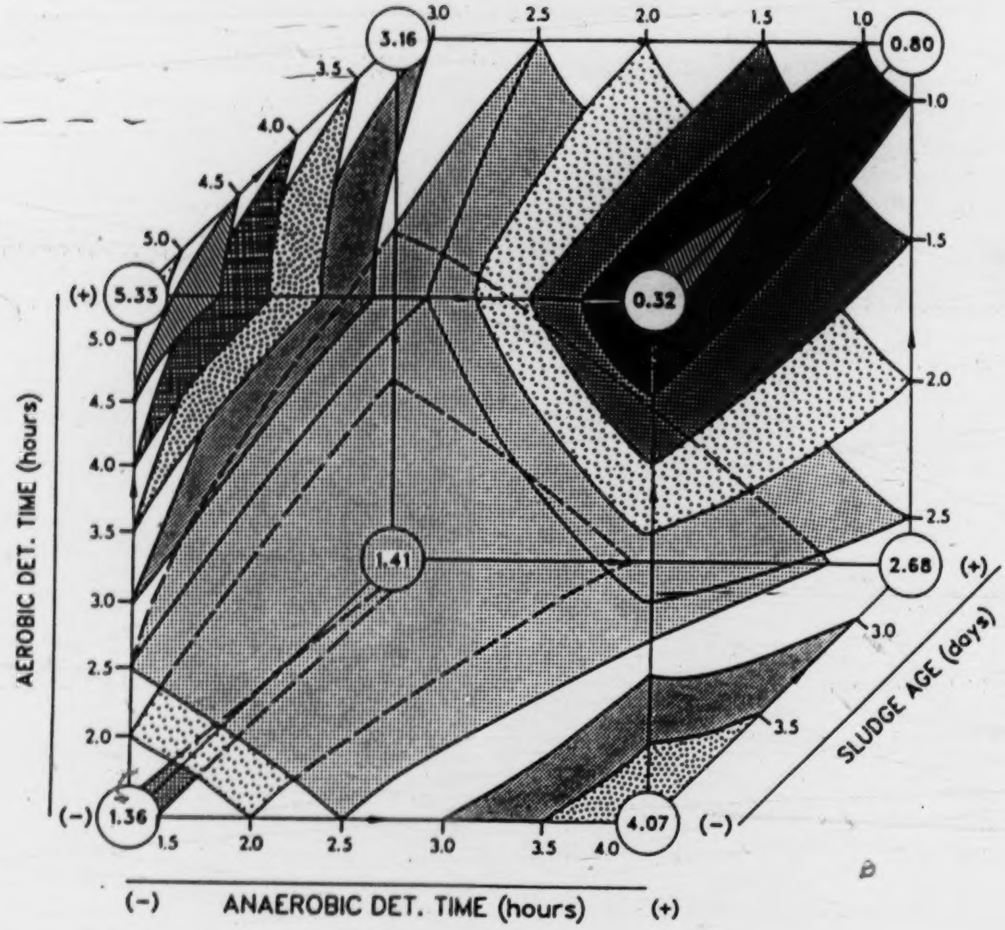
Note: See page 112 for a full explanation of this figure.

Figure 6.8 Estimated Response Surface for $PO_4$-P Removal Factorial Design, (Day 6).


2.79
2.46
2.5
2.5
3.0
(+) 3.17
2.63
3.0
AEROBIC DET. TIME (hours)
2.5
0.57
2.0
2.21
(+)
2.5
SLUDGE AGE (days)
(-) 2.01
2.5
2.94
(-)
(-)
ANAEROBIC DET. TIME (hours)
(+)

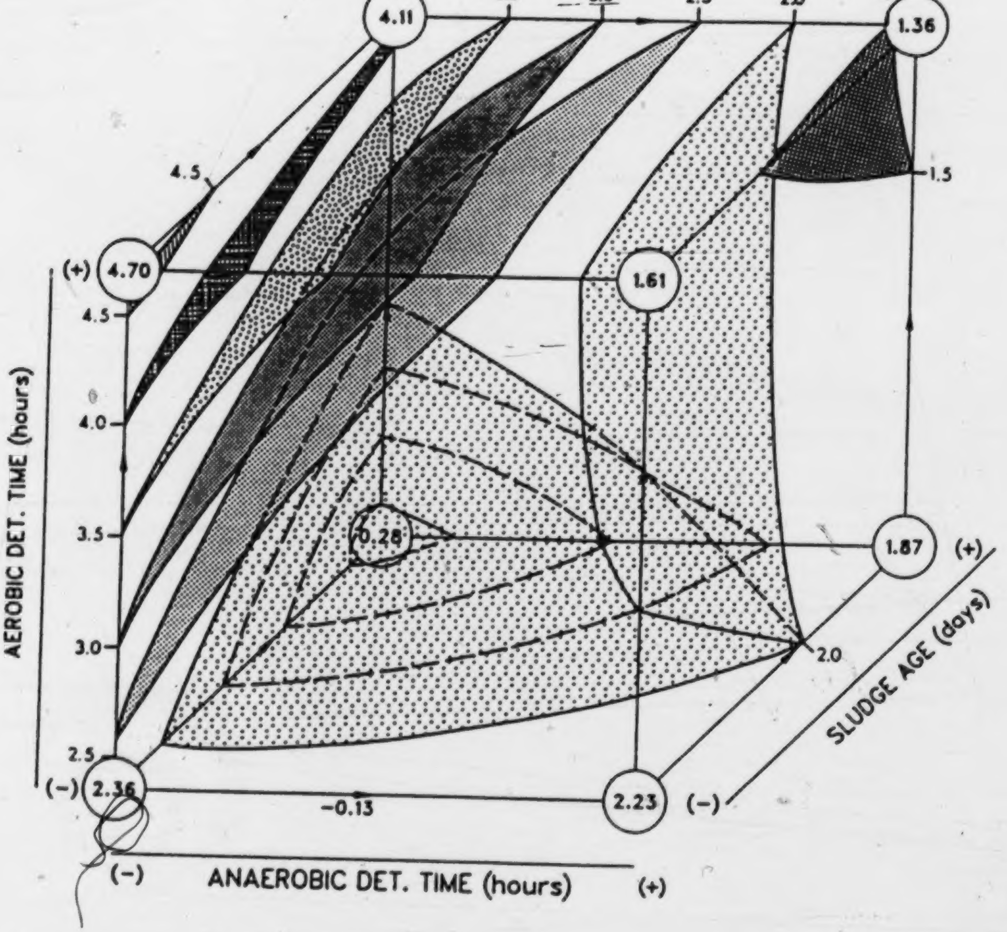
Note. See page 112 for a full explanation of this figure.

Figure 6.9 Estimated Response Surface for $PO_4$-P Removal Factorial Design, (Day 7).



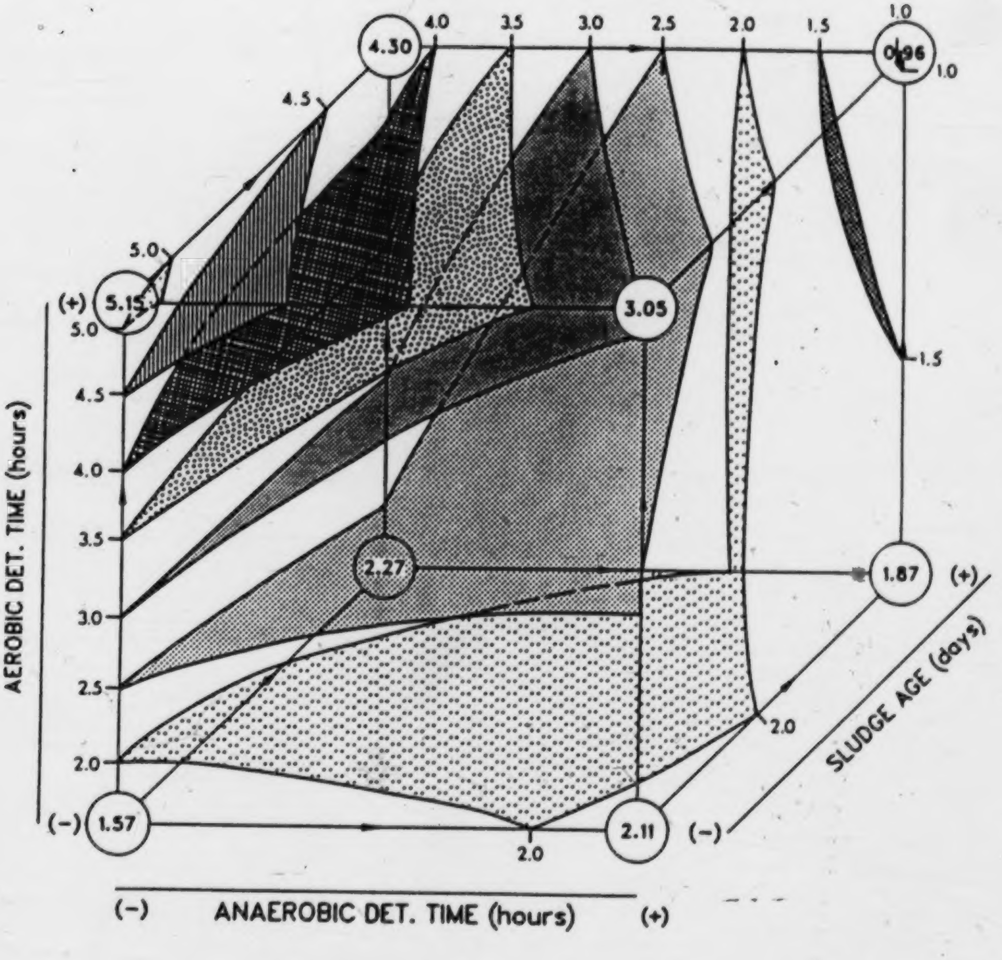
Note: See page 112 for a full explanation of this figure.

Figure 6.10 Estimated Response Surface for $PO_4$-P Removal Factorial Design, (Day 9).



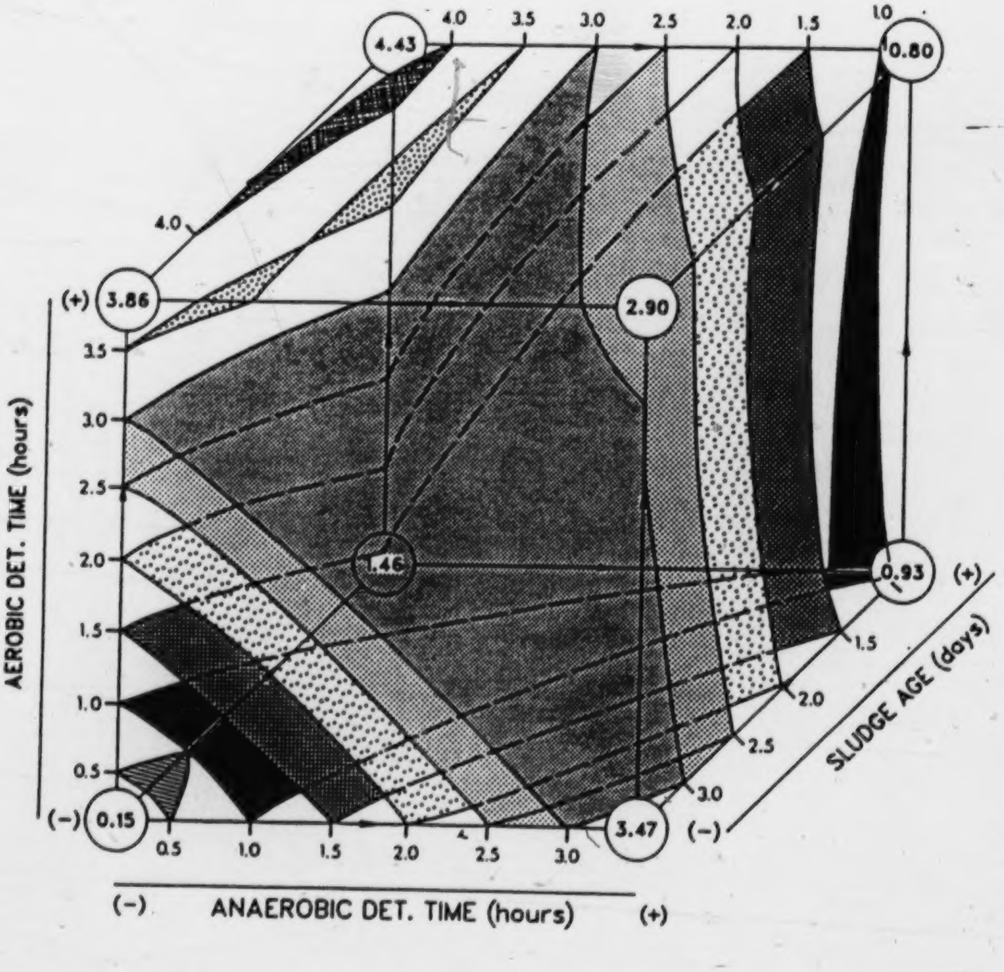
Note: See page 112 for a full explanation
of this figure.

Figure 6.11 Estimated Response Surface for $PO_4$-P Removal Factorial Design, (Day 10).



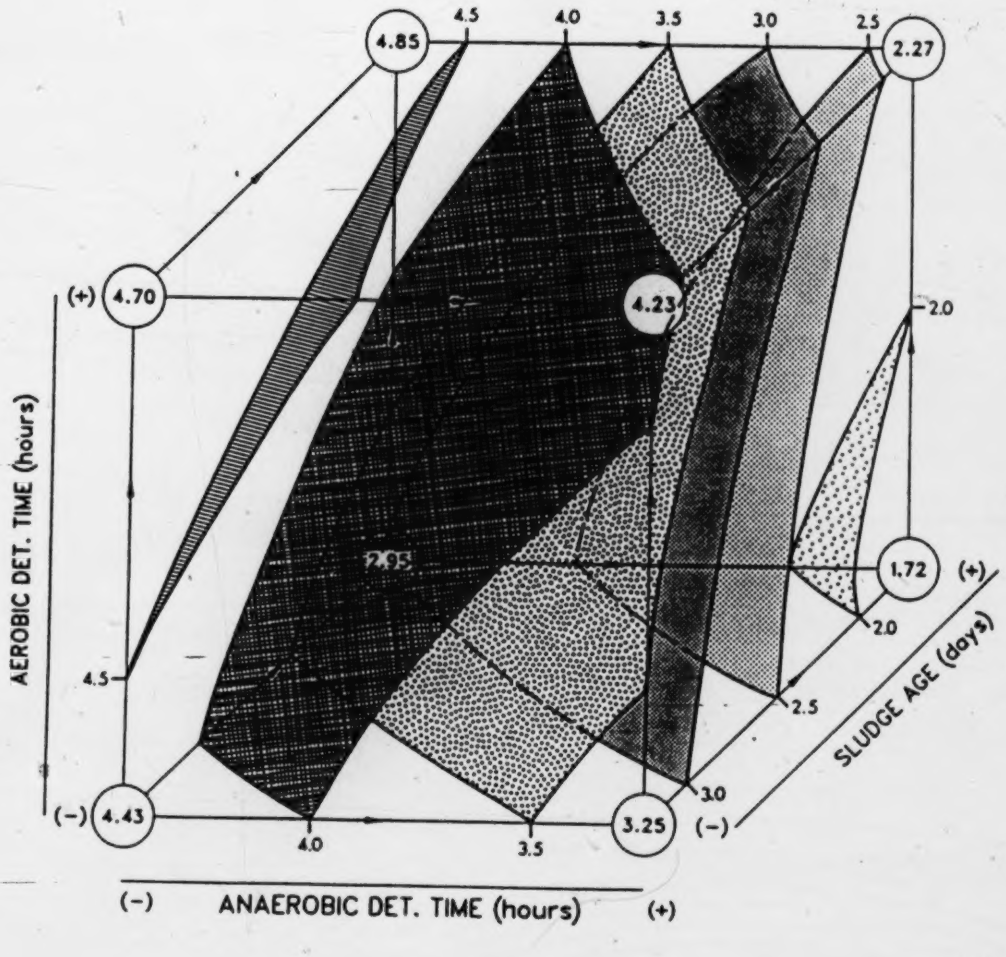
Note: See page 112 for a full explanation of this figure.

Figure 6.12 Estimated Response Surface for $PO_4$-P Removal Factorial Design, (Day 11).



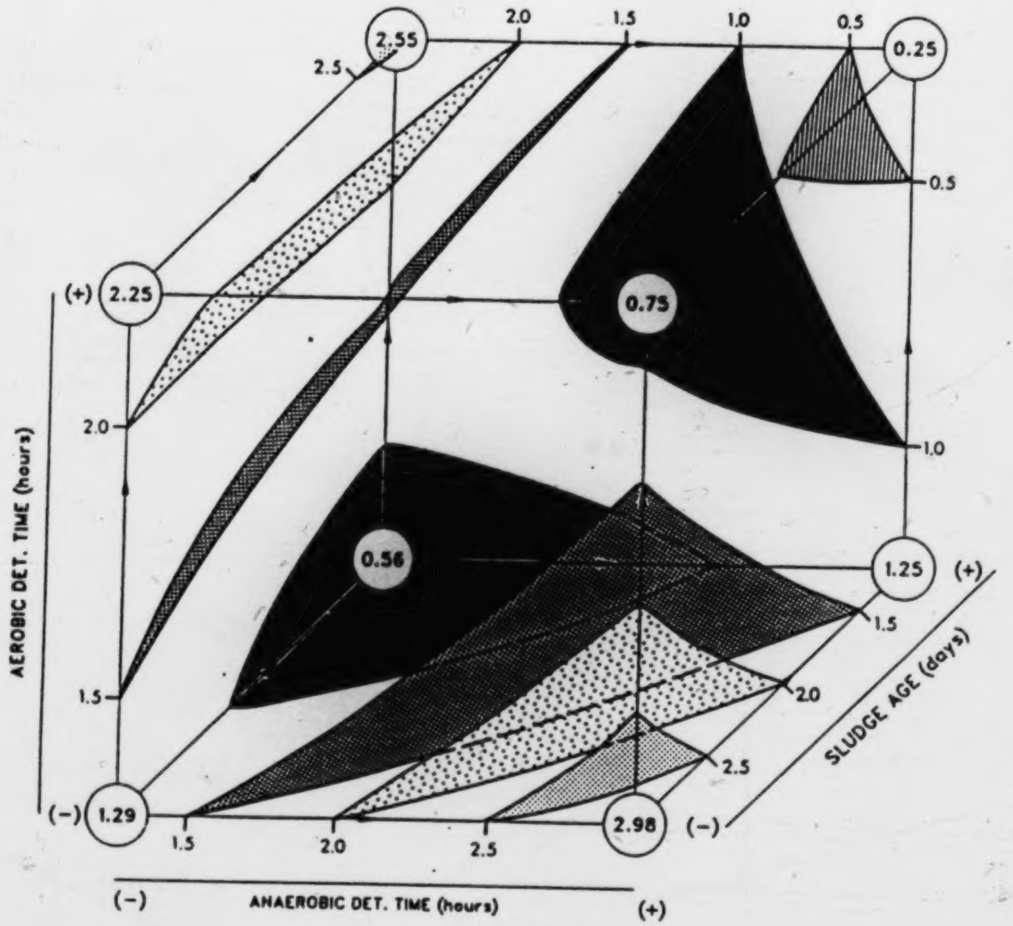
Note: See page 112 for a full explanation of this figure.

Figure 6.13 Estimated Response Surface for $PO_4$-P Removal Factorial Design, (Day 12).



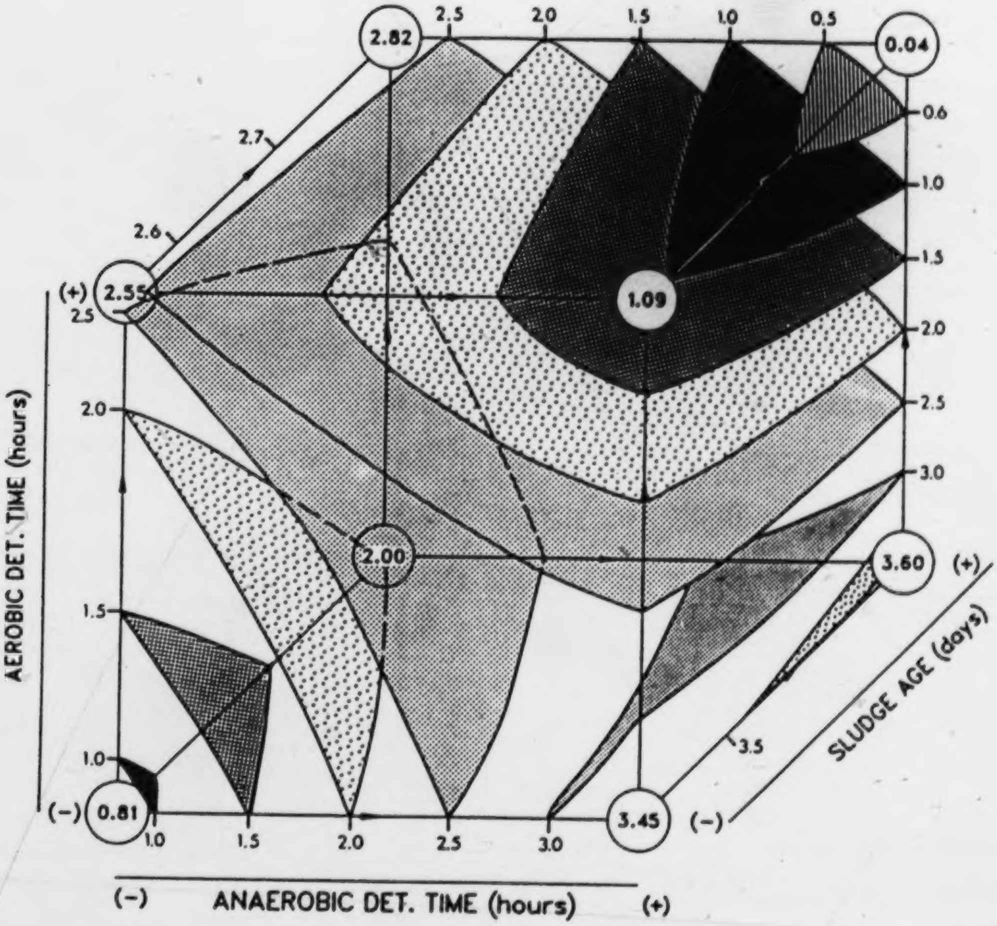
Note: See page 112 for a full explanation of this figure.

Figure 6.14 Estimated Response Surface for $PO_4$-P Removal Factorial Design, (Day 13).



Note: See page 112 for a full explanation of this figure.

Figure 6.15 Estimated Response Surface for $PO_4$-P Removal Factorial Design, (Day 14).



Note: See page 112 for a full explanation of this figure.

Figure 6.16 Estimated Response Surface for $PO_4$-P Removal Factorial Design, (Day 15).

# 7. CONCLUSIONS

The bench scale biological phosphorus removal study using a factorial design experimental procedure has yielded interesting and useful results. The following conclusions are based on this experimental procedure with consideration of other work available in the literature.

1. The experimental results obtained show the process to be a complex one, which does not lend itself easily to the formation of a predictive model based on the parameters monitored in this project. The extent of biological phosphorus removal appears to be a function of both the controlled variables investigated and other unidentified factors. It is strongly suspected that compositional variation in the influent wastewater plays an important role in the success of the removal process.
2. The factors investigated in the experimental program have been shown definitely to influence the achievable phosphorus removal level. The level of removal does not however seem to vary linearly with changes in these factors.
3. Of the three parameters studied the setting of the aerobic detention time has a significant influence on the biological phosphorus removal process. The sludge age setting is also significant but to a lesser extent. Of greatest importance however is the high significance of the interaction between aerobic and anaerobic detention times. The implication of this is that the

maintenance of a favourable ratio between aerobic and anaerobic detention times is more critical than the choice of setting for either one. While this finding appears to be valid approximately 80% of the time it must be noted that variation with wastewater composition is indicated.

4. On the basis of the results obtained a high level setting for each of the three parameters is indicated as the most favourable combination.
5. The experimental results show that in all cases good phosphorus release in the anaerobic zone must proceed good uptake within the aerobic zone. This result is in good agreement with the literature reports of other researchers.
6. Monitoring of oxidation-reduction potential through the reactors showed that it has little value as a tool by which to predict the level of phosphorus release or uptake. The trend by which phosphorus release took place when the ORP was highly negative and uptake occurred during positive ORP conditions is important, even if definite required maxima and minima cannot be established.
7. From observed and reported cyclic reactor performance there appears to be a need for better understanding of variation in the incoming wastewater characteristics. This suspected variation was considered responsible for serious fluctuations in the effluent quality. The

magnitude of the aerobic/anaerobic detention time interaction was also seen to be affected.

8. The biological phosphorus removal process as tested was not extremely stable or consistent in performance. Even the best performing system had periods during which effluent phosphorus concentration exceeded the objective value of 1 mg/L even though the bench scale units were operated at steady state hydraulic conditions.

   Taking the above into account it still must be noted that process scale-up may help to stabilize performance.

9. Removal of organic carbonaceous substrate, as measured by COD, was also considered. The level of removal improved with higher aerobic detention time settings but was found to be adversely affected by increases in anaerobic detention time. At the levels studied the sludge age did not appear to have any significant effect on COD removal. Therefore slight deterioration in COD removal might be expected under the conditions indicated as optimal for biological phosphorus removal, over the range studied.

10. Regardless of the overall level of COD removal most of the removal took place in the anaerobic zones of the reactors. It therefore seems that the bacteria responsible for COD removal are unaffected by the system of alternating aerobic and anaerobic conditions.

11. Volatile solids production was seen to increase through

the reactors thereby indicating the ability of the bacteria to adapt to the various conditions applied.

12. $BOD_5$ (BOD5) testing proved inconclusive in examining the parameter effects on carbonaceous substrate removal. This may be due to the lack of precision inherent in the test.

# 8. RECOMMENDATIONS

1. The bench scale pilot plant reactors all achieved a level of biological phosphorus removal. They were however prone to sporadic deterioration in effluent phosphorus concentration. Considering the better performing reactors this deterioration was attributed to influences external to the designed experiment, with variation in influent wastewater characteristics suspected. Since this variation alters the system performance so dramatically it is strongly recommended that further study be carried out in order to better characterize fluctuation in parameter values and the effects of this variation on the biological phosphorus removal process.

   A particular possibility for investigation is the variation of effluent $PO_4$-P concentration with influent COD values. Preliminary observation indicates an inversely related cyclical variation relationship between these parameters.

2. The bench scale studies indicate that the aerobic and anaerobic detention times in a biological phosphorus removing activated sludge system should not be chosen individually. The measured results suggest that long aerobic detention times should be accompanied by long anaerobic detention times. The full scale pilot study at the Gold Bar Wastewater Treatment Plant operates with a two hour (one pass) anaerobic detention time and a six

hour (three pass) aerobic detention time. Since in the bench scale experiment a combination of detention times of 40% anaerobic and 60% aerobic proved most successful it may therefore be beneficial to balance the detention times to provide three hours (one and a half passes) anaerobic detention time and five hours (two and a half passes) of aerobic detention time.

3. While the experimental study showed that the SRT setting was not critical to the process, the higher SRT did provide some improvement in phosphorus removal. Therefore some advantage may be gained in operating the full scale plant at a higher SRT.
4. A system for hydraulic detention time control would likely prove beneficial to the phosphorus removal process. Reduction in flow volumes, particularly at weekends, may contribute to greater nitrification and consequent reduction of anaerobiosis levels thereby affecting phosphorus effluent quality. Flow control would also afford the maximum possible operator control on the process.
5. If the biological phosphorus removal process is to be used then the practice of returning digester supernatant to the headworks of the plant should be discontinued. Presently this leads to recirculation of phosphorus which is leached out during the digestion process. As an alternative a stripping tank utilizing chemical precipitation of the high phosphorus concentrations

contained in the supernatant could be introduced.

6. Literature findings infer that every effort should be made to discourage nitrification within the biological phosphorus removal process unless separate steps are taken to ensure nitrogen removal. It should be noted however that the experimental results neither confirm nor refute these findings.

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# APPENDIX I

## EQUIPMENT AND MATERIALS

A schematic representation of the layout of the biological phosphorus removal bench-scale experiment is shown in Figure I.1. The overall experiment incorporated systems for the collection and treatment of domestic, settled wastewater and the discharge of the treated effluent. The entire experimental treatment system was housed in an on-site pilot plant trailer at the Gold Bar Wastewater Treatment Plant. The components of the various systems are examined in detail below.

## BENCH SCALE PLANT INFLUENT COLLECTION AND DISTRIBUTION

Effluent from the full-scale primary clarifiers at the Gold Bar Wastewater Treatment Plant was used as influent to the bench scale treatment system. A submersible pump in the distribution channel to the full-scale aeration chambers pumped the primary effluent to a central 1 $m^3$ fibre glass collection vat within the trailer. Float-control switches within the vat regulated the frequency of pumping.

A small submersible pump within the collection vat continuously raised the wastewater to a styrofoam-insulated steel constant-head tank which was elevated to a height of approximately two metres above floor level. Since flow to the ten reactors was by gravity the maintenance of a constant discharge pressure head helped to regulate the discharge flowrate. The excess flow to the constant-head tank was returned to the central collection vat via an overflow spout and PVC piping. This return pipe was designed to avoid aeration of the wastewater. Due to the low rate of wastewater withdrawal to the secondary reactors this circulation was necessary to maintain solids suspension and to provide mixing. The float control switches in the central collection vat were positioned such that fresh primary influent was injected every three to four hours approximately.

A distribution manifold system brought the wastewater through individual tygon tubing lines to each of the ten reactors. Each line was equipped with a flow control valve to regulate the reactor inflow rate. Regular cleaning of the feed lines with alternating solutions of hydrochloric acid and sodium hydroxide was carried out.

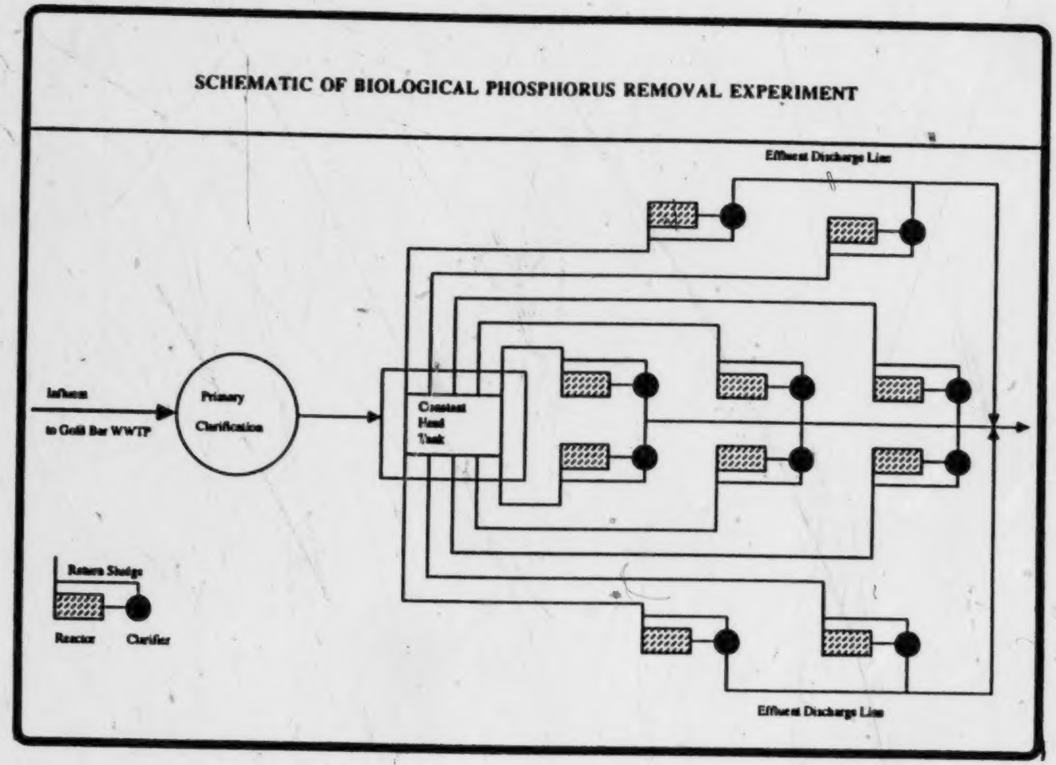

SCHEMATIC OF BIOLOGICAL PHOSPHORUS REMOVAL EXPERIMENT
Effluent Discharge Line
Influent
to Gold Bar WWTP
Primary Clarification
Constant Head Tank
Return Sludge
Reactor
Clarifier
Effluent Discharge Line

Figure I.1 Schematic Layout of Bench Scale Biological Phosphorus Removal Experiment.

## SECONDARY TREATMENT SYSTEM

### REACTORS

Secondary treatment was provided in bench-scale plexiglass reactors. Each reactor had a total capacity of 67 litres and was divided into ten interconnected cells. Plan and side profile views are shown in Figures I.2 and I.3, respectively. These figures also show the flow path through the reactor. It was originally intended to provide a one hour detention time per cell at a total flow rate of 8 litres per hour (133 mL/min) however constructional restraints reduced this to 0.84 hours (50 min).

Eight litres per hour was considered the minimum flow rate which could be consistently maintained. This flow consisted of two thirds primary influent and one third return sludge. The total detention time required in each individual reactor was determined by the factorial design settings. These detention times were set by blocking off the extra cells. Thus the reactor with the shortest detention time consisted of three cells in series while the reactor with the longest detention time utilized all ten cells. The utilized capacity was subdivided into anaerobic cells and aerobic cells.

In order to check the mixing performance of the reactors dye studies were carried out on the reactors with the shortest and longest detention times. The reactors were modelled as complete-mix stirred tank reactors (CSTR) in series with each cell considered a CSTR. The theoretical effluent dye concentration from the final cell was calculated from Equation I.1

$$C_i = \frac{C_0}{(n-1)!} (n\theta)^{i-1} e^{-n\theta} \qquad [I.1]$$

(Metcalf & Eddy, 1979)

where

i = final cell number (i.e. 3 or 10)

n = number of CSTR's in series

$\theta$ = $t/t_0$, normalized time

$t_0$ = overall nominal detention time in the n reactors

t = time measured from the addition of dye tracer

$C_i$ = dye concentration in the first cell

$C_0$ = final cell effluent dye concentration

The results of the dye tests for the three cell and ten cell reactors are shown in Figures I.4 and I.5, respectively. In both cases the overall detention time, as represented by the centre of gravity mean value, correspnded well with the calculated theoretical detention time. Note that Figure I.4 shows dye recovery in excess of that theoretically possible. This is probably due to calibration drift in the dye monitor or variation in the influent dye concentration. This displaces the concentration values slightly but does not affect the detention time (X-axis) values.

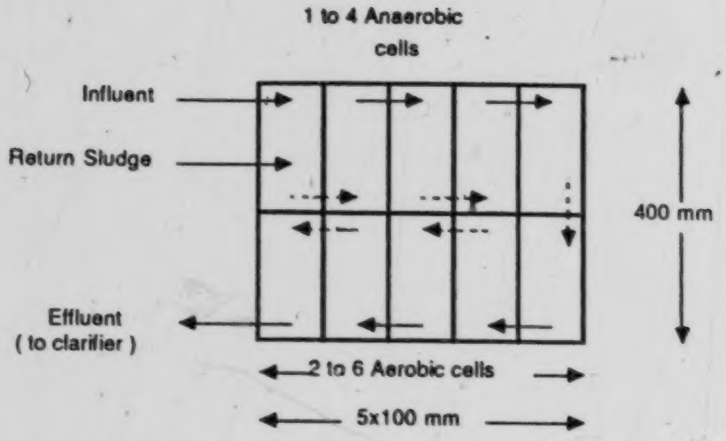
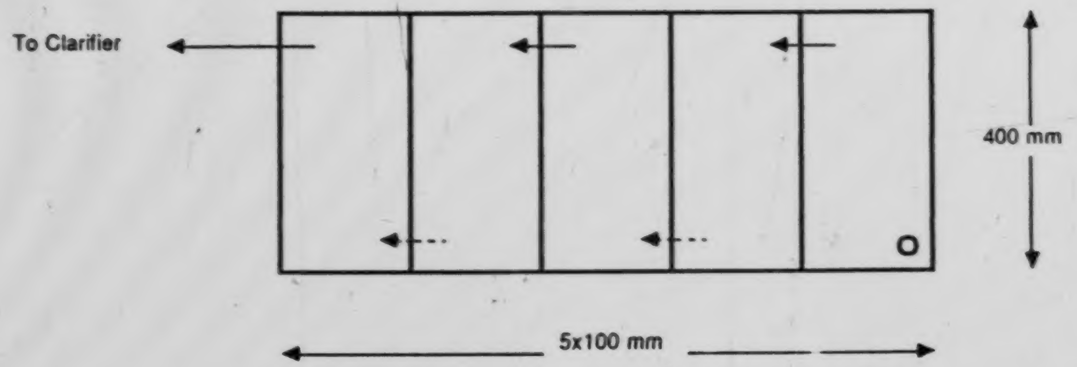

1 to 4 Anaerobic cells
Influent
Return Sludge
400 mm
Effluent ( to clarifier )
2 to 6 Aerobic cells
5x100 mm

Figure I.2 Plan View Schematic of Secondary Reactor used in Biological Phosphorus Removal Study


To Clarifier
400 mm
5x100 mm

(Arrows indicate flow direction)

Figure I.3 Side Profile Schematic of Secondary Reactor

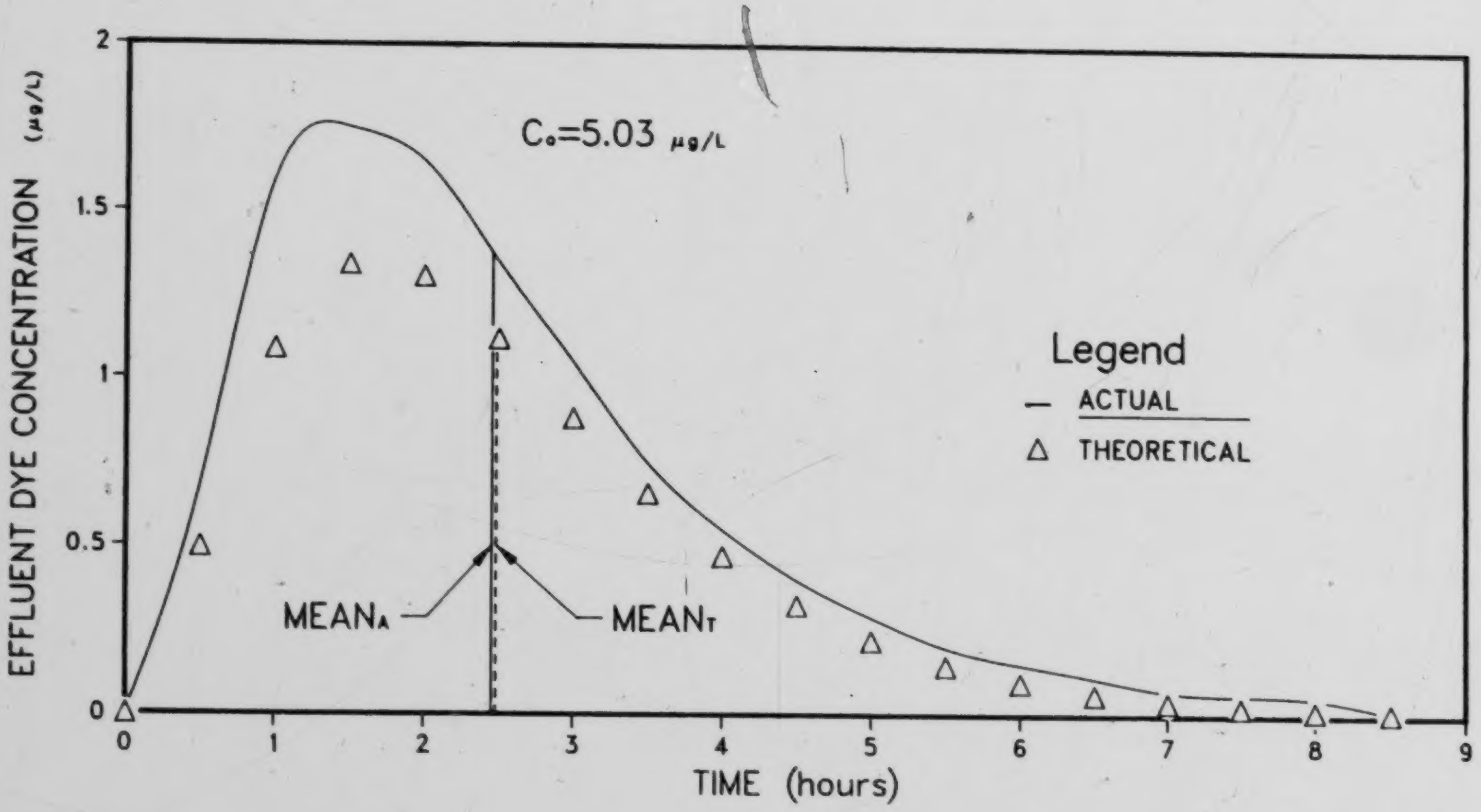


Figure I.4 Theoretical and Actual Effluent Dye Concentration From Three Cell Reactor

## MIXING

In the aerobic cells a 1 h.p. Campbell-Hausfeld compressor provided aeration through a control manifold and air-stone system. The capacity of this compressor was more than sufficient to satisfy the requirements of aeration and mixing.

In the anaerobic cells top mounted 64 rpm Howard Industrial Co. stirring motors, with double bladed shafts, provided continuous mixing and suspension with a minimum entrapment of air.

## CLARIFICATION

Final clarification from each reactor was provided by a two hour detention time plexiglass clarifier. The sludge surface loading rate was 0.19 m/hour. Effluent was discharged, by gravity, to waste over an overflow weir. The settled sludge was returned to the first anaerobic cell in each reactor. A small propeller system provided slight agitation of the settled sludge to avoid channelling of the return sludge effluent through the sludge blanket. The clarifier system is shown in Figure I.6.

## SLUDGE CONTROL

Return sludge pumping was provided by four Cole-Palmer Masterflex peristaltic pumps. All the settled sludge was returned to the reactors and wasting was carried out on a volume basis directly from the reactors. Sludge was returned at the same rate (2.67 litres per hour, approximately) to the first cell of each reactor. Sludge wasting, from the

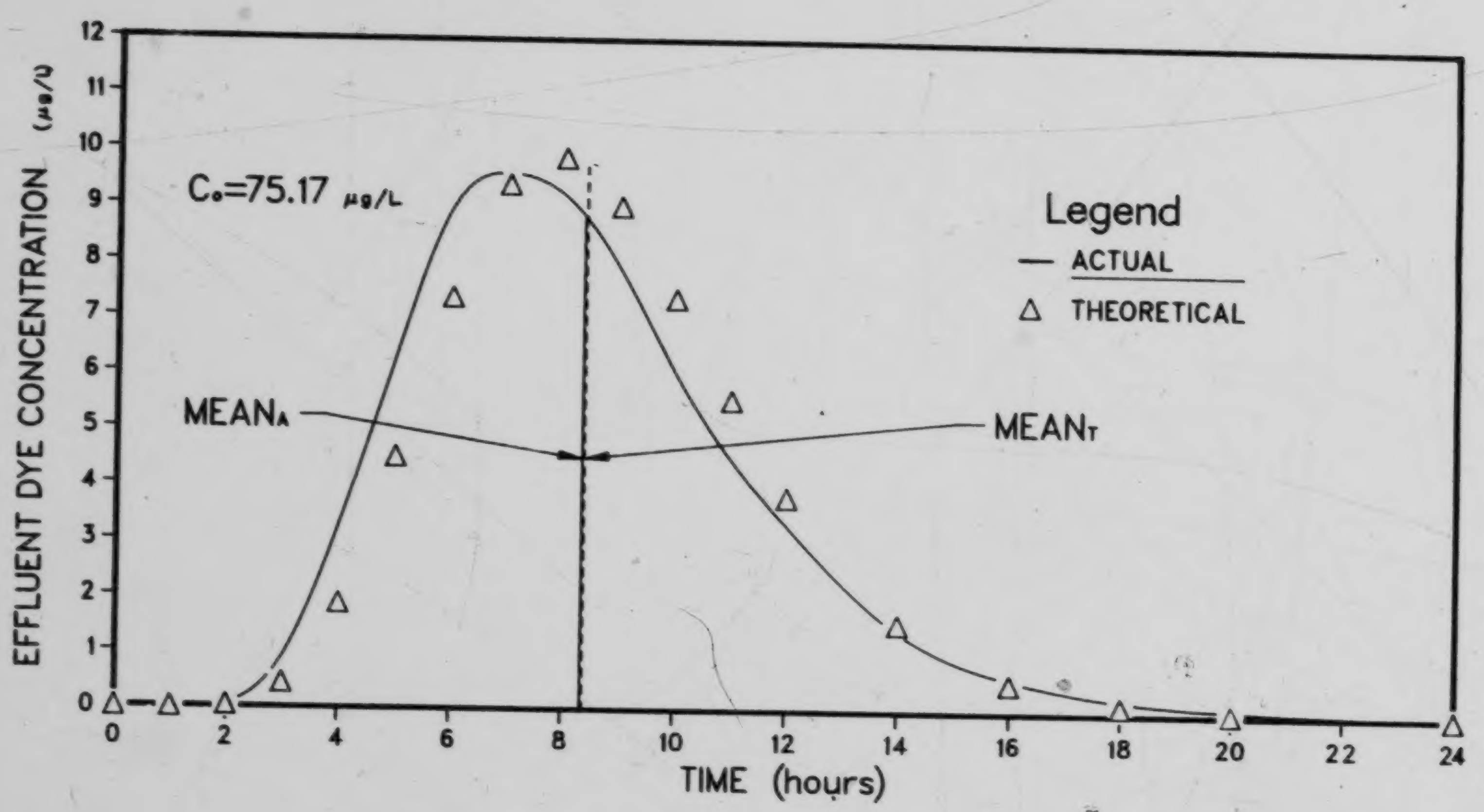


Figure I.5 Theoretical and Actual Effluent Dye Concentration From Ten Cell Reactor

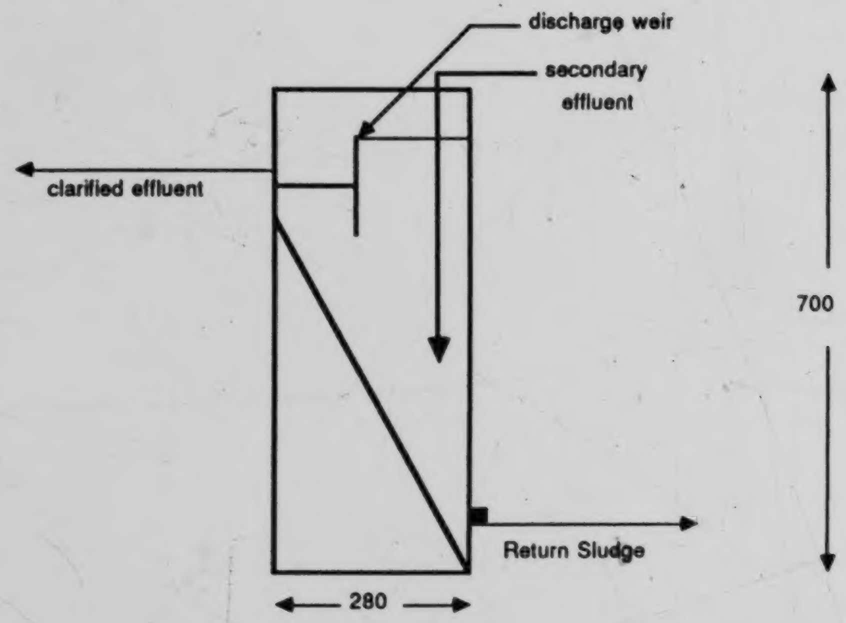

discharge weir
secondary effluent
clarified effluent
700
Return Sludge
280

Figure I.6 Schematic of Secondary Clarifier used in Biological Phosphorus Removal Study (dimensions in mm, width 150 mm)

reactors, was carried out using sludge age as a process control variable.

# APPENDIX II

## ANALYTICAL TESTING METHODS

Most of the analytical procedures followed throughout the experimental program were as outlined in Standard Methods for the Examination of Water and Wastewater, 16 Ed., 1985. These procedures are listed and referenced in Table II.1.

Total phosphorus concentrations were determined in the Gold Bar Wastewater Treatment Plant Laboratory. Soluble orthophosphate-phosphorus concentrations were determined by the stannous chloride method and in the Gold Bar Wastewater Treatment Plant laboratory by the ascorbic acid method. Statistical tests on the results of common sample analyses revealed no significant difference between the methods. All nitrate and nitrite determinations were made using the Gold Bar Wastewater Treatment Plant automatic analyser. Instrumented analyses carried out are listed in Table II.2.

Table II.1 Standard Methods used in Biological Phosphorus Removal Study

| Parameter | Test Method | Standard Methods Test Number |
|---|---|---|
| BOD | Oxygen Demand (Biochemical) | 507 |
| COD | Open Reflux Method | 508A |
| $PO_4$-P | Preliminary Filtration Step | 424A |
| | Stannous Chloride Method | 424E |
| $PO_4$-P | Preliminary Filtration Step | 424A |
| | Ascorbic Acid Method | 424F |
| Total Phosphorus | Preliminary Digestion Step | 424C |
| | Ascorbic Acid Method | 424F |
| TSS | Total Suspended Solids Dried at 103-105°C | 209C |
| VSS | Fixed and Volatile Solids ignited at 550°C | 209D |

Table II.2 Instrumented Analysis used in the Biological Phosphorus Removal Study

| Parameter | Instruments |
|---|---|
| Dissolved Oxygen | YSI (Yellow Spring Instrument Co.) Dissolved Oxygen Meter |
| pH | Hach Model 16400 pH meter |
| ORP | Orion 399A pH meter<br>Orion Redox Probe (Calomel reference) |
| $NO_2$-N | Technicon Automatic Analyser II |
| $NO_3$-N | Technicon Automatic Analyser II |

## ANALYTICAL TESTING SCHEDULE

During the first four days of the intense sampling program all effluent samples were withdrawn from the secondary clarifier discharge flow. While conditions in the secondary clarifier would not affect filtered BOD or COD readings it was realized that adverse clarifier conditions could affect the effluent $PO_4$-P concentrations. Stress conditions within the clarifier could cause phosphorus release which would overshadow efficient process uptake within the secondary reactor.

Since process optimization was the primary aim of the experimental study the $PO_4$-P concentration in the secondary reactor effluent was considered to better reflect the influence of the variable settings. Therefore from day 5 (October 11, 1985) dissolved $PO_4$-P samples were withdrawn from the final aerobic cell of each reactor. Ten individual factorial analyses were considered the minimum required and it was therefore considered necessary to extend the collection of dissolved $PO_4$-P samples for a further four days to day 15 (October 21, 1985). The ten sample days from October 7, 1985 to October 17th were used in the estimation of the other process parameters. Samples were not taken on Monday, October 14, which was a public holiday.

# APPENDIX III

## SUMMARY

A listing of the data obtained from the bench-scale biological phosphorus removal study is shown below. The results of the various parameter determinations are presented for the pre-testing monitoring period and for the intense sampling period. The results of supplemental testing including parameter estimation profiles through each reactor is also shown. Tabulation of the factorial analysis for each day is also provided.

Graphical presentations of various parameter contrasts are also included. Note that for calculation purposes a higher number of significant figures were retained than might necessarily be expected to result from the analytical methods used. Also on several instances, due to time restrictions or errors in analysis, results were unavailable. A hyphen ("-") is used in the Tables to denote these instances. In the graphical presentations wherever values are suspected to be in error they are joined to the other points by a dashed line.

**Table III.1 Paramerer Values Obtained During Pretesting monitoring period.**

MONITORING PERIOD

1985

Filtered COD, mg/L

| Reactor Number | Aug. 19 | Aug. 21 | Aug. 26 | Aug. 30 | Sept. 3 | Sept. 5 | Sept. 9 | Sept. 11 | Sept. 13 | Sept. 16 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 53 | 82 | 60 | 54 | 72 | - | 39 | 71 | 43 | 67 |
| 2 | 44 | 88 | 65 | 42 | 78 | 28 | 31 | 55 | 36 | 39 |
| 3 | 49 | 68 | 59 | 50 | 75 | 21 | 35 | 39 | 67 | 68 |
| 4 | 40 | 61 | 95 | 40 | 81 | 39 | 47 | 35 | 28 | 59 |
| 5 | 67 | 61 | 51 | 40 | 69 | 53 | 31 | 27 | 36 | 33 |
| 6 | - | 38 | 56 | 48 | 72 | 25 | 27 | 20 | 18 | 23 |
| 7 | - | 93 | 51 | 52 | 83 | 36 | 35 | 55 | 46 | 57 |
| 8 | - | 84 | 56 | 40 | 86 | 25 | 39 | 24 | 46 | 37 |
| 9 | 44 | 84 | 67 | 52 | 81 | 28 | 43 | 27 | 50 | 43 |
| 10 | 71 | 72 | 64 | - | 81 | 25 | 35 | 24 | 18 | 18 |
| Primary Effluent | 74 | - | 77 | 168 | 144 | 114 | 82 | 157 | 91 | 70 |

Table III.1 (Continued)

MONITORING PERIOD

1985

Filtered COD, mg/L

| Reactor Number | Sept. 20 | Sept. 23 | Sept. 27 | Sept. 30 | Oct. 2 |
|---|---|---|---|---|---|
| 1 | 46 | 33 | 80 | 48 | 61 |
| 2 | 52 | 39 | 32 | 48 | 57 |
| 3 | 56 | 49 | 44 | 48 | 96 |
| 4 | 60 | 45 | 32 | 48 | 96 |
| 5 | 72 | 37 | 116 | 75 | 92 |
| 6 | 42 | 60 | 36 | 34 | 55 |
| 7 | 92 | 56 | 40 | 42 | 96 |
| 8 | 52 | 33 | 40 | 51 | 47 |
| 9 | 80 | 37 | 44 | 51 | 39 |
| 10 | 40 | 21 | 36 | 36 | 45 |
| Primary Effluent | 128 | 93 | 132 | 113 | 122 |

## Table III.1 (Continued)

### MONITORING PERIOD

### 1985

Soluble $PO_4$-P, mg/L

| Reactor Number | Sept. 4 | Sept. 6 | Sept. 12 | Sept. 24 | Sept. 27 | Sept. 30 | Oct. 2 | Oct. 3 | Oct. 4 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.3 | 3.3 | 4.7 | 2.7 | 5.2 | 10.5 | 2.7 | 3.5 | 2.5 |
| 2 | 3.9 | 3.3 | 5.6 | 2.1 | 4.1 | 6.1 | 3.5 | 3.7 | 4.2 |
| 3 | 2.4 | 2.4 | 5.6 | 5.6 | 3.1 | 4.5 | 6.3 | 4.8 | 4.4 |
| 4 | 5.0 | 3.2 | 4.7 | 0.3 | 1.0 | 11.1 | 5.7 | 6.4 | 2.1 |
| 5 | 2.3 | 3.3 | 1.4 | 1.8 | 5.2 | 8.3 | 5.0 | 4.7 | 4.4 |
| 6 | 3.8 | 4.1 | 4.7 | 3.1 | 2.5 | 5.2 | 4.8 | 2.1 | 2.7 |
| 7 | 2.6 | 4.3 | 5.6 | 9.0 | 7.8 | 6.4 | 4.8 | 4.8 | 1.1 |
| 8 | 5.5 | 5.0 | 3.6 | 0.3 | 6.0 | 9.1 | 1.8 | 0.4 | 1.5 |
| 9 | 3.7 | 3.0 | 5.6 | 1.8 | 7.5 | 8.0 | 3.1 | 4.0 | 5.0 |
| 10 | 4.2 | 3.9 | 5.6 | 5.0 | 3.9 | 4.8 | 4.3 | 4.5 | 3.4 |
| Primary Effluent | 3.7 | 3.6 | 4.4 | 5.0 | 5.0 | 4.7 | 9.6 | 5.3 | 4.3 |

### Table III.1 (Continued)

### MONITORING PERIOD

### 1985

$NO_3$-N, mg/L

| Reactor Number | Sept. 23 |
|---|---|
| 1 | 1.47 |
| 2 | 3.34 |
| 3 | <0.03 |
| 4 | 0.73 |
| 5 | <0.03 |
| 6 | 7.03 |
| 7 | <0.03 |
| 8 | 1.33 |
| 9 | 0.36 |
| 10 | 12.82 |
| Primary Effluent | <0.03 |

Table III.2 Paramerer Values Obtained During Intense Testing Period.

TESTING PERIOD

October 7, 1985

| Reactor Number | Total P mg/L | Sol. P mg/L | $COD_f$ mg/L | $COD_{uf}$ mg/L | $BOD_f$ mg/L | $BOD_{uf}$ mg/L | TSS mg/L | VSS mg/L | $NO_3$-N mg/L | $NO_2$-N mg/L |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | - | - | 47 | 150 | 2 | 71 | 115 | 103 | <0.03 | <0.03 |
| 2 | - | - | 38 | 34 | 6 | 9 | 33 | 25 | 14.14 | 0.07 |
| 3 | - | - | 48 | 141 | 5 | 68 | 63 | 62 | <0.03 | 0.04 |
| 4 | - | - | 69 | - | 3 | 30 | 37 | 35 | 2.4 | 3.07 |
| 5 | - | - | 55 | 110 | 10 | 31 | 40 | 30 | <0.03 | <0.04 |
| 6 | - | - | 45 | 50 | 4 | 19 | 10 | 5 | 10.91 | 2.31 |
| 7 | - | - | 77 | 117 | 11 | 71 | 58 | 47 | <0.03 | <0.04 |
| 8 | - | - | 76 | 72 | 3 | 23 | 18 | 13 | 8.66 | 3.01 |
| 9 | - | - | 76 | 64 | 5 | 22 | 28 | 22 | 2.58 | 2.46 |
| 10 | - | - | 63 | 63 | 3 | 29 | 23 | 18 | 19.91 | 0.89 |
| Primary Effluent | - | - | 134 | 249 | 55 | 150 | 102 | 95 | <0.03 | 0.04 |

## Table III.2 (Continued)

### TESTING PERIOD

### October 8, 1985

| Reactor Number | Total P mg/L | Sol. $PO_4$-P mg/L | $COD_f$ mg/L | $COD_{uf}$ mg/L | $BOD_f$ mg/L | $BOD_{uf}$ mg/L | TSS mg/L | VSS mg/L | $NO_3$-N mg/L | $NO_2$-N mg/L |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | - | - | 78 | 127 | 17 | 68 | 43 | 37 | <0.03 | <0.04 |
| 2 | - | - | 49 | 61 | 1 | 67 | 20 | 15 | 13.27 | 0.68 |
| 3 | - | - | 72 | 116 | 13 | 56 | 53 | 40 | <0.03 | <0.04 |
| 4 | - | - | 43 | 66 | 1 | 27 | 25 | 25 | 1.61 | 1.21 |
| 5 | - | - | 90 | 137 | 11 | 50 | 43 | 32 | <0.03 | <0.04 |
| 6 | - | - | 42 | 60 | 6 | 23 | 20 | 5 | 9.58 | 1.84 |
| 7 | - | - | 63 | 64 | 6 | 23 | 25 | 13 | <0.03 | 0.08 |
| 8 | - | - | 45 | 54 | 3 | 18 | 18 | 13 | 7.89 | 2.48 |
| 9 | - | - | 45 | 63 | 2 | 22 | 20 | 15 | 3.56 | 1.82 |
| 10 | - | - | 52 | 56 | 4 | 7 | 20 | 15 | 11.60 | 1.64 |
| Primary Effluent | - | - | 214 | 346 | 94 | 294 | 97 | 78 | <0.03 | 0.04 |

## Table III.2 (Continued)

TESTING PERIOD

October 9, 1985

| Reactor Number | Total P mg/L | Sol. $PO_4$-P mg/L | $COD_f$ mg/L | $COD_{uf}$ mg/L | $BOD_f$ mg/L | $BOD_{uf}$ mg/L | TSS mg/L | VSS mg/L | $NO_3$-N mg/L | $NO_2$-N mg/L |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | - | - | 57 | 70 | 8 | 25 | 27 | 18 | <0.03 | 0.26 |
| 2 | - | - | 40 | 40 | 1 | 7 | 13 | 8 | 8.94 | 1.92 |
| 3 | - | - | 39 | 87 | 5 | 53 | 35 | 25 | 0.12 | 0.06 |
| 4 | - | - | 38 | 49 | 2 | 29 | 17 | 15 | 1.81 | 1.78 |
| 5 | - | - | 56 | 124 | 4 | 69 | 58 | 48 | <0.03 | <0.04 |
| 6 | - | - | 40 | 58 | 2 | 52 | 43 | 28 | 12.16 | 0.54 |
| 7 | - | - | 51 | 43 | 7 | 14 | 8 | 8 | 8.24 | 3.20 |
| 8 | - | - | 51 | 43 | 7 | 14 | 8 | 8 | 8.24 | 3.20 |
| 9 | - | - | 44 | 63 | 1 | 18 | 18 | 12 | 11.72 | 4.20 |
| 10 | - | - | 40 | 40 | 3 | 3 | 12 | 8 | 7.46 | 2.05 |
| Primary Effluent | - | - | 179 | 529 | 80 | 222 | 243 | 187 | <0.03 | 0.041 |

Table III.2 (Continued)

TESTING PERIOD

October 10, 1985

| Reactor Number | Total P mg/L | Sol. $PO_4$-P mg/L | $COD_f$ mg/L | $COD_{uf}$ mg/L | $BOD_f$ mg/L | $BOD_{uf}$ mg/L | TSS mg/L | VSS mg/L | $NO_3$-N mg/L | $NO_2$-N mg/L |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | - | - | 55 | 86 | 5 | 46 | 48 | 42 | <0.03 | 0.04 |
| 2 | - | - | 35 | 40 | 4 | 7 | 18 | 12 | 14.22 | 0.20 |
| 3 | - | - | 54 | 82 | 10 | 47 | 37 | 27 | 0.03 | 0.05 |
| 4 | - | - | 43 | 55 | 1 | 30 | 18 | 13 | 1.31 | 2.40 |
| 5 | - | - | 66 | 108 | 12 | 45 | 43 | 38 | <0.03 | 0.04 |
| 6 | - | - | 23 | 27 | 4 | 10 | 13 | 8 | 14.74 | 0.41 |
| 7 | - | - | 50 | 53 | 8 | 30 | 25 | 20 | <0.03 | 0.05 |
| 8 | - | - | 43 | 43 | 5 | 19 | 17 | 13 | 6.68 | 2.40 |
| 9 | - | - | 43 | 58 | 15 | 28 | 18 | 13 | 6.68 | 2.40 |
| 10 | - | - | 43 | 43 | 5 | 19 | 17 | 13 | 6.68 | 2.40 |
| Primary Effluent | - | - | 173 | 339 | 93 | 178 | 80 | 63 | <0.03 | <0.04 |

## Table III.2 (Continued)

### TESTING PERIOD

### October 11, 1985

| Reactor Number | Total P mg/L | Sol. $PO_4$-P mg/L | $COD_t$ mg/L | $COD_{ut}$ mg/L | $BOD_t$ mg/L | $BOD_{ut}$ mg/L | TSS mg/L | VSS mg/L | $NO_3$-N mg/L | $NO_2$-N mg/L |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5.29 | 1.29 | 47 | 99 | 5 | 40 | 48 | 42 | 0.09 | <0.04 |
| 2 | 3.81 | 2.25 | 3 | 11 | 6 | 7 | 12 | 7 | 11.95 | 0.215 |
| 3 | 4.46 | 2.98 | 58 | 106 | 6 | 37 | 35 | 27 | 0.16 | <0.04 |
| 4 | 1.14 | 0.75 | 30 | 39 | 6 | 14 | 15 | 20 | 7.94 | 2.87 |
| 5 | 5.56 | 0.56 | 51 | 137 | 6 | 51 | 60 | 45 | 0.12 | <0.04 |
| 6 | 4.56 | 2.55 | 19 | 144 | 6 | 69 | 147 | 112 | 11.96 | 0.76 |
| 7 | 4.38 | 1.25 | 58 | 141 | 8 | 33 | 47 | 38 | 0.41 | 0.43 |
| 8 | 1.92 | 0.25 | 39 | 19 | 6 | 24 | 20 | 15 | 8.14 | 1.86 |
| 9 | 2.56 | 0.42 | 31 | 36 | 6 | 22 | 17 | 12 | 7.30 | 2.25 |
| 10 | 4.62 | 2.83 | 28 | 31 | 6 | 53 | 12 | 12 | 9.41 | 1.84 |
| Primary Effluent | 7.61 | 5.17 | 226 | 342 |  | 178 | 80 | 65 | 0.06 | <0.04 |

## Table III.2 (Continued)

### TESTING PERIOD

### October 12, 1985

| Reactor Number | Total P mg/L | Sol. $PO_4$-P mg/L | $COD_f$ mg/L | $COD_{uf}$ mg/L | $BOD_f$ mg/L | $BOD_{uf}$ mg/L | TSS mg/L | VSS mg/L | $NO_3$-N mg/L | $NO_2$-N mg/L |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.40 | 0.81 | 47 | 69 | 8 | 26 | 26 | 17 | <0.03 | 0.09 |
| 2 | 3.39 | 2.55 | 46 | 103 | 7 | 51 | 73 | 58 | 13.10 | 0.12 |
| 3 | 6.01 | 3.45 | 47 | 90 | 7 | 51 | 68 | 62 | <0.03 | <0.04 |
| 4 | 3.55 | 1.09 | 59 | 51 | 4 | 21 | 18 | 12 | 9.64 | 3.52 |
| 5 | 5.00 | 2.00 | 71 | 99 | 15 | 37 | 45 | 37 | <0.03 | <0.04 |
| 6 | 5.33 | 2.82 | 55 | 77 | 4 | 51 | 60 | 46 | 12.13 | 0.16 |
| 7 | 5.05 | 3.60 | 47 | 95 | 6 | 38 | 85 | 73 | 0.04 | 0.21 |
| 8 | 0.88 | 0.04 | 39 | 59 | 4 | 18 | 18 | 13 | 8.66 | 2.21 |
| 9 | 1.26 | 0.33 | 95 | 68 | 6 | 21 | 23 | 18 | 4.99 | 1.95 |
| 10 | 4.38 | 2.68 | 56 | 68 | 5 | 13 | 13 | 5 | 11.36 | 1.92 |
| Primary Effluent | 7.32 | 4.74 | 154 | 293 | 86 | 165 | 155 | 120 | <0.03 | <0.04 |

## Table III.2 (Continued)

### TESTING PERIOD

### October 13, 1985

| Reactor Number | Total P mg/L | Sol. $PO_4$-P mg/L | $COD_t$ mg/L | $COD_{ut}$ mg/L | $BOD_t$ mg/L | $BOD_{ut}$ mg/L | TSS mg/L | VSS mg/L | $NO_3$-N mg/L | $NO_2$-N mg/L |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5.02 | 1.31 | 56 | 80 | 11 | 25 | 40 | 32 | <0.03 | 0.11 |
| 2 | 6.53 | 4.66 | 41 | 49 | 4 | 22 | 22 | 17 | 15.98 | 0.13 |
| 3 | 5.14 | 4.13 | 66 | - | 7 | 48 | 42 | 28 | 0.29 | 0.04 |
| 4 | 7.58 | 1.79 | 52 | 68 | 6 | 67 | 13 | 12 | 7.43 | 3.05 |
| 5 | 3.28 | 0.30 | 57 | 87 | 7 | 28 | 68 | 58 | 0.75 | 0.09 |
| 6 | 6.40 | 4.87 | 18 | 45 | 5 | 16 | 10 | 8 | 15.66 | 0.17 |
| 7 | 7.13 | 3.30 | 57 | 87 | 7 | 28 | 56 | 58 | 0.75 | 0.09 |
| 8 | 2.45 | 1.47 | 40 | 62 | 5 | 23 | 18 | 15 | 7.26 | 3.05 |
| 9 | 2.55 | 1.47 | 40 | 52 | 5 | 16 | 15 | 12 | 11.05 | 2.13 |
| 10 | 2.45 | 0.28 | 40 | 52 | 5 | 16 | 15 | 12 | 11.05 | 2.13 |
| Primary Effluent | 7.96 | 4.59 | 123 | 216 | 51 | 185 | 67 | 58 | <0.03 | <0.04 |

### Table III.2 (Continued)

### TESTING PERIOD

### October 15, 1985

| Reactor Number | Total P mg/L | Sol. $PO_4$-P mg/L | $COD_f$ mg/L | $COD_{uf}$ mg/L | $BOD_f$ mg/L | $BOD_{uf}$ mg/L | TSS mg/L | VSS mg/L | $NO_3$-N mg/L | $NO_2$-N mg/L |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.90 | 2.58 | 27 | 37 | 4 | 30 | 23 | 17 | 0.19 | 0.43 |
| 2 | 5.93 | 5.43 | 38 | 48 | 5 | 60 | 23 | 22 | 16.46 | 0.109 |
| 3 | 3.02 | 1.92 | 52 | 82 | 1 | 21 | 44 | 35 | 0.06 | 0.27 |
| 4 | 5.98 | 3.42 | 41 | 66 | 1 | 16 | 20 | 13 | 10.39 | 1.95 |
| 5 | 3.13 | 2.13 | 33 | 44 | 6 | 23 | 15 | 12 | <0.03 | 0.17 |
| 6 | 4.09 | 3.29 | 33 | 41 | 5 | 19 | 98 | 77 | 12.31 | 0.20 |
| 7 | 3.35 | 1.76 | 46 | 85 | 1 | 21 | 70 | 58 | 0.14 | 0.40 |
| 8 | 6.09 | 3.62 | 37 | 93 | 1 | 46 | 47 | 37 | 10.41 | 0.78 |
| 9 | 4.63 | 3.26 | 37 | 47 | 1 | 14 | 10 | 10 | 13.91 | 0.45 |
| 10 | 5.46 | 3.42 | 28 | 32 | 1 | 2 | 0 | 0 | 16.29 | 0.31 |
| Primary Effluent | 4.77 | 2.87 | 77 | 172 | 23 | 261 | 100 | 65 | <0.03 | <0.04 |

## Table III.2 (Continued)

### TESTING PERIOD

### October 16, 1985

| Reactor Number | Total P mg/L | Sol. $PO_4$-P mg/L | $COD_f$ mg/L | $COD_{uf}$ mg/L | $BOD_f$ mg/L | $BOD_{uf}$ mg/L | TSS mg/L | VSS mg/L | $NO_3$-N mg/L | $NO_2$-N mg/L |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.91 | 2.01 | 50 | 56 | 5 | 22 | 32 | 25 | 0.59 | 0.45 |
| 2 | - | 3.17 | 38 | 67 | 3 | 13 | 32 | 23 | 6.47 | 0.10 |
| 3 | 3.68 | 2.94 | 64 | 86 | 8 | 20 | 20 | 17 | 0.03 | 0.06 |
| 4 | 3.34 | 2.63 | 40 | 63 | 1 | 49 | 28 | 20 | 10.49 | 3.23 |
| 5 | 1.69 | 0.57 | 55 | 90 | 8 | 20 | 47 | 37 | 0.49 | 0.42 |
| 6 | - | 2.79 | 39 | 49 | 2 | 19 | 25 | 22 | 7.87 | 0.82 |
| 7 | 1.93 | 2.21 | 45 | 73 | 6 | 19 | 17 | 17 | 0.63 | 0.38 |
| 8 | 2.72 | 2.46 | 32 | 56 | 1 | 20 | 10 | 10 | 13.74 | 2.50 |
| 9 | 3.60 | 2.00 | 30 | 51 | 3 | 7 | 23 | 15 | 8.86 | 0.62 |
| 10 | 4.40 | 3.93 | 33 | 51 | 1 | 1 | 7 | 3 | 11.72 | 0.23 |
| Primary Effluent | - | 3.90 | 161 | 292 | 95 | 294 | 102 | 82 | <0.03 | 0.06 |

## Table III.2 (Continued)

### TESTING PERIOD

### October 17, 1985

| Reactor Number | Total P mg/L | Sol. $PO_4$-P mg/L | $COD_t$ mg/L | $COD_{uf}$ mg/L | $BOD_t$ mg/L | $BOD_{uf}$ mg/L | TSS mg/L | VSS mg/L | $NO_3$-N mg/L | $NO_2$-N mg/L |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.80 | 1.36 | 34 | 54 | 3 | 14 | 28 | 15 | 0.24 | <0.04 |
| 2 | 6.40 | 5.33 | 54 | 134 | 3 | 30 | 32 | 27 | 3.40 | 1.63 |
| 3 | 5.26 | 4.07 | 93 | 65 | 10 | 24 | 29 | 20 | 0.03 | <0.04 |
| 4 | 4.06 | 0.32 | 32 | 43 | 1 | 35 | 15 | 12 | 13.73 | 0.61 |
| 5 | 2.24 | 1.41 | 36 | 51 | 4 | 20 | 20 | 18 | 0.15 | 0.26 |
| 6 | 5.15 | 3.16 | 33 | 134 | 1 | 41 | 120 | 98 | 11.85 | 1.74 |
| 7 | 4.43 | 2.68 | 38 | 61 | 4 | 14 | 28 | 27 | <0.03 | <0.04 |
| 8 | 4.21 | 1.21 | 26 | 49 | 4 | 14 | 13 | 7 | 5.95 | 3.56 |
| 9 | 1.38 | 0.88 | 25 | 44 | 2 | 22 | 28 | 20 | 12.80 | 0.63 |
| 10 | 3.54 | 3.34 | 25 | 33 | 2 | 18 | 12 | 8 | 8.62 | 3.69 |
| Primary Effluent | 5.64 | 4.21 | 157 | 263 | 96 | 175 | 88 | 67 | <0.03 | <0.04 |

## Table III.2 (Continued)

### TESTING PERIOD

### October 18, 1985

| Reactor Number | Soluble $PO_4$-P, mg/L |
|---|---|
| 1 | 2.36 |
| 2 | 4.70 |
| 3 | 2.23 |
| 4 | 1.61 |
| 5 | 0.28 |
| 6 | 4.11 |
| 7 | 1.87 |
| 8 | 1.36 |
| 9 | - |
| 10 | 1.36 |
| Primary Effluent | 4.85 |

Table III.2 (Continued)

TESTING PERIOD

October 19, 1985

| Reactor Number | Soluble $PO_4$-P, mg/L |
|---|---|
| 1 | 1.57 |
| 2 | 5.15 |
| 3 | 2.11 |
| 4 | 3.05 |
| 5 | 2.27 |
| 6 | 4.30 |
| 7 | 1.87 |
| 8 | 0.96 |
| 9 | - |
| 10 | 0.96 |
| Primary Effluent | 5.00 |

## Table III.2 (Continued)

TESTING PERIOD

October 20, 1985

| Reactor Number | Soluble $PO_4$-P, mg/L |
|---|---|
| 1 | 0.15 |
| 2 | 3.86 |
| 3 | 3.47 |
| 4 | 2.90 |
| 5 | 1.46 |
| 6 | 4.43 |
| 7 | 0.93 |
| 8 | 0.80 |
| 9 | - |
| 10 | 0.80 |
| Primary Effluent | 4.70 |

Table III.2 (Continued)

TESTING PERIOD

October 21, 1985

| Reactor Number | Soluble $PO_4$-P, mg/L |
|---|---|
| 1 | 4.43 |
| 2 | 4.70 |
| 3 | 3.25 |
| 4 | 4.23 |
| 5 | 2.95 |
| 6 | 4.85 |
| 7 | 1.72 |
| 8 | 2.27 |
| 9 | - |
| 10 | 2.27 |
| Primary Effluent | 4.85 |

Table III.3 Paramerer Values Obtained in Profile Sampling Throughout Each Reactor.

PROFILE DATA SHEET

Run #1

| | | | | | | Cell Number | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | PE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $PO_4$-P (mg/L) (filtered) | 5.31 | 10.07 | 5.99 | 3.41 | | | | | | | |
| TOTAL-P (mgP/L) (unfiltered) | 6.54 | 39.26 | 39.93 | 39.72 | | | | | | | |
| COD (mg/L) (GFC-Filtered) | 199 | 76 | 47 | 39 | | | | | | | |
| TSS (mg/L) | | 1590 | 1525 | 1920 | | | | | | | |
| VSS (mg/L) | 1355 | 1220 | 1560 | | | | | | | | |
| DISSOLVED OXYGEN (mg/L) | 0.2 | 3.8 | 4.6 | | | | | | | | |
| REDOX POTENTIAL (mV) | -310 | -150 | -90 | | | | | | | | |
| pH | 7.5 | 7.7 | 7.8 | | | | | | | | |

## Table III.3 (Continued)

## PROFILE DATA SHEET

### Run #2

|  |  |  |  |  | Cell Number |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  | PE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $PO_4$-P (mg/L) (filtered) | 5.09 | 8.87 | 9.36 | 6.72 | 4.87 | 3.96 | 3.66 | 3.47 |  |  |  |
| TOTAL-P (mgP/L) (unfiltered) |  | 23.62 | 38.96 | 43.25 | 40.03 | 41.67 | 37.42 | 37.73 |  |  |  |
| COD (mg/L) (GFC-Filtered) | 182 | 69 | 58 | 60 | 50 | 52 | 47 | 43 |  |  |  |
| TSS (mg/L) |  | 1045 | 1105 | 1510 | 1190 | 845 | 1095 | 1030 |  |  |  |
| VSS (mg/L) |  | 875 | 910 | 1255 | 985 | 680 | 880 | 835 |  |  |  |
| DISSOLVED OXYGEN (mg/L) |  | 0.1 | 0.2 | 1.7 | 2.3 | 2.0 | 4.4 | 5.7 |  |  |  |
| REDOX POTENTIAL (mV) |  | -180 | -125 | -70 | -35 | -10 | -5 | +5 |  |  |  |
| pH |  | - | - | - | - | - | - |  |  |  |  |

## Table III.3 (Continued)

## PROFILE DATA SHEET

## Run #3

| | | | | | | Cell Number | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | PE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $PO_4$-P (mg/L) (filtered) | 3.58 | 6.10 | 4.85 | 3.81 | 4.11 | 2.82 | 1.76 | | | | |
| TOTAL-P (mgP/L) (unfiltered) | - | - | - | - | - | - | | | | | |
| COD (mg/L) (GFC-Filtered) | 74 | 33 | 55 | 219 | 30 | 37 | 48 | | | | |
| TSS (mg/L) | 176 | 1150 | 900 | 550 | 480 | 860 | 1390 | | | | |
| VSS (mg/L) | 124 | 908 | 730 | 470 | 390 | 720 | 1130 | | | | |
| DISSOLVED OXYGEN (mg/L) | | 0 | 0 | 0 | 0 | 5.8 | 7.1 | | | | |
| REDOX POTENTIAL (mV) | | -285 | -295 | -295 | -265 | -90 | -65 | | | | |
| pH | | 7.5 | 7.5 | 7.6 | 7.6 | 7.9 | 8.1 | | | | |

## Table III.3 (Continued)

## PROFILE DATA SHEET

### Run #4

| | | | | | Cell Number | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $PO_4$-P (mg/L) (filtered) | 4.25 | 6.18 | 7.73 | 10.01 | 10.08 | 3.89 | 2.99 | 2.39 | 2.28 | 2.10 | 1.94 |
| TOTAL-P (mgP/L) (unfiltered) | | 47.16 | 59.69 | 47.93 | 45.09 | 42.72 | 39.19 | 47.38 | 48.16 | 45.48 | 51.61 |
| COD (mg/L) (GFC-Filtered) | 101 | 56 | 35 | 63 | 51 | 44 | 33 | 40 | 48 | 47 | 37 |
| TSS (mg/L) | | 955 | 1150 | 1075 | 940 | 1005 | 875 | 1040 | 1170 | 965 | 1240 |
| VSS (mg/L) | | 745 | 905 | 855 | 765 | 790 | 665 | 815 | 915 | 735 | 955 |
| DISSOLVED OXYGEN (mg/L) | | 0 | 0 | 0 | 0 | 2.3 | 4.3 | 5.3 | 4.0 | 5.5 | 5.3 |
| REDOX POTENTIAL (mV) | | -150 | -170 | -170 | -120 | -75 | -30 | 0 | +10 | +25 | +30 |
| pH | | 7.4 | 7.3 | 7.2 | 7.2 | 7.3 | 7.4 | 7.4 | 7.3 | 7.3 | 7.4 |

### Table III.3 (Continued)

### PROFILE DATA SHEET

### Run #5

|  |  |  |  |  |  | Cell Number |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  | PE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $PO_4$-P (mg/L) (filtered) | 5.69 | 8.65 | 4.99 | 2.36 |  |  |  |  |  |  |  |
| TOTAL-P (mgP/L) (unfiltered) |  | 8.45 | 33.28 | 32.44 | 44.59 |  |  |  |  |  |  |
| COD (mg/L) (GFC-Filtered) | 191 | 165 | 102 | 99 |  |  |  |  |  |  |  |
| TSS (mg/L) |  | 1130 | 1095 | 1635 |  |  |  |  |  |  |  |
| VSS (mg/L) |  | 930 | 920 | 1355 | 735 | 955 |  |  |  |  |  |
| DISSOLVED OXYGEN (mg/L) |  | 0.1 | 1.1 | 1.4 |  |  |  |  |  |  |  |
| REDOX POTENTIAL (mV) |  | -320 | -140 | -8.5 | 0 | +10 | +25 | +30 |  |  |  |
| pH |  | 6.8 | 7.0 | 7.1 |  |  |  |  |  |  |  |

## Table III.3 (Continued)

## PROFILE DATA SHEET

### Run #6

| | | | | | Cell Number | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $PO_4$-P (mg/L) (filtered) | 4.10 | 4.72 | 4.05 | 3.83 | 3.52 | 3.40 | 3.24 | 3.32 | | | |
| TOTAL-P (mgP/L) (unfiltered) | | 21.17 | 22.55 | 23.16 | 20.86 | 27.91 | 22.70 | 28.37 | | | |
| COD (mg/L) (GFC-Filtered) | 130 | 55 | 46 | 44 | 34 | 100 | 34 | 39 | | | |
| TSS (mg/L) | | 890 | 900 | 1150 | 1255 | 1360 | 1250 | | | | |
| VSS (mg/L) | | 720 | 745 | 935 | 1030 | 1100 | 860 | 1000 | | | |
| DISSOLVED OXYGEN (mg/L) | | 0 | 1.3 | 2.4 | 3.8 | 1.5 | 3.9 | 4.6 | | | |
| REDOX POTENTIAL (mV) | | -245 | -90 | -75 | -55 | -45 | -40 | -35 | | | |
| pH | | 7.7 | 7.6 | 7.4 | 7.4 | 7.3 | 7.3 | 7.4 | | | |

Table III.3 (Continued)

PROFILE DATA SHEET

Run #7

| | PE | 1 | 2 | 3 | 4 | Cell Number 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $PO_4$-P (mg/L) (filtered) | 4.31 | 7.02 | 8.17 | 8.34 | 8.42 | 5.86 | 4.17 | | | | |
| TOTAL-P (mgP/L) (unfiltered) | | 28.07 | 29.60 | 28.22 | 26.07 | 23.93 | 20.71 | | | | |
| COD (mg/L) (GFC-Filtered) | 154 | 89 | 108 | 130 | 118 | 197 | 50 | | | | |
| TSS (mg/L) | | 1080 | 1160 | 1030 | 935 | 905 | 785 | | | | |
| VSS (mg/L) | | 910 | 985 | 875 | 795 | 765 | 680 | | | | |
| DISSOLVED OXYGEN (mg/L) | | | | | | | | | | | |
| REDOX POTENTIAL (mV) | | | | | | | | | | | |
| pH | | | | | | | | | | | |

## Table III.3 (Continued)

## PROFILE DATA SHEET

## Run #8

| | PE | 1 | 2 | 3 | 4 | Cell Number 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $PO_4$-P (mg/L) (filtered) | 3.87 | 10.48 | 11.46 | 11.15 | 8.14 | 4.33 | 1.75 | 0.31 | 0.23 | 0.04 | 0.05 |
| TOTAL-P (mgP/L) (unfiltered) | | 48.82 | 47.04 | 42.69 | 31.70 | 30.68 | 27.10 | 27.76 | 43.64 | 48.85 | 29.97 |
| COD (mg/L) (GFC-Filtered) | 113 | 63 | 48 | 43 | 40 | 44 | 40 | 36 | 44 | 47 | 40 |
| TSS (mg/L) | 1510 | 920 | 1080 | 945 | 760 | 880 | 790 | 1455 | 565 | 1895 | |
| VSS (mg/L) | 1210 | 730 | 900 | 755 | 615 | 700 | 625 | 1150 | 455 | 1520 | |
| DISSOLVED OXYGEN (mg/L) | | 0.1 | 0 | 0 | 0 | 3.4 | 1.6 | 3.8 | 1.9 | 4.2 | 4.0 |
| REDOX POTENTIAL (mV) | | -115 | -230 | -240 | -190 | -75 | -50 | -30 | -15 | -15 | -5 |

Table III.3 (Continued)

PROFILE DATA SHEET

Run #8 (Continued)

| | Cell Number<br>PE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | | 6.2 | 6.2 | 6.3 | 6.5 | 6.6 | 6.6 | 6.7 | 6.7 | 6.8 | 6.8 |

## Table III.3 (Continued)

## PROFILE DATA SHEET

## Run #9

| | PE | 1 | 2 | 3 | 4 | Cell Number 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $PO_4$-P (mg/L) (filtered) | 2.23 | 3.88 | 3.16 | 3.24 | 3.37 | 3.69 | 3.80 | 3.91 | 4.01 | | |
| TOTAL-P (mgP/L) (unfiltered) | | 44.48 | 44.63 | 47.55 | 42.95 | 43.87 | 50.46 | 65.18 | 61.50 | | |
| COD (mg/L) (GFC-Filtered) | 86 | 22 | 85 | 26 | 28 | 26 | 33 | 33 | 30 | | |
| TSS (mg/L) | | 1255 | 1295 | 1390 | 1310 | 1005 | 1260 | 8060 | 1615 | | |
| VSS (mg/L) | | 980 | 1005 | 1090 | 1020 | 775 | 965 | 7077 | 1240 | | |
| DISSOLVED OXYGEN (mg/L) | | 0.1 | 0.1 | 3.6 | 4.3 | 4.8 | 5.9 | 7.0 | 7.1 | | |
| REDOX POTENTIAL (mV) | | -25 | -25 | 0 | +20 | +25 | +30 | +30 | +35 | | |
| pH | | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.3 | 7.5 | 7.6 | | |

## Table III.3 (Continued)

## PROFILE DATA SHEET

### Run #10

| | | | | | Cell Number | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $PO_4$-P (mg/L) (filtered) | 3.22 | 3.53 | 3.52 | 3.75 | 3.77 | 3.92 | 4.08 | 3.95 | 4.06 | | |
| TOTAL-P (mgP/L) (unfiltered) | | 24.23 | 34.20 | 26.53 | 29.29 | 25.61 | 27.91 | 25.77 | 33.59 | | |
| COD (mg/L) (GFC-Filtered) | 135 | 32 | 33 | 43 | 32 | 44 | 39 | 35 | 38 | | |
| TSS (mg/L) | 965 | 1290 | 1080 | 1200 | 1005 | 1085 | 755 | 1410 | | | |
| VSS (mg/L) | | 125 | 780 | 1050 | 870 | 960 | 805 | 870 | 605 | 1130 | |
| DISSOLVED OXYGEN (mg/L) | | | | | | | | | | | |
| REDOX POTENTIAL (mV) | | | | | | | | | | | |
| pH | | | | | | | | | | | |

Table III.4 Complete Listing of Factorial Analyses Carried Out for PO$_4$-P Removal From Testing Period Data

Factorial Analysis    Day #5

| | | |
|---|---|---|
| Main Effects | 1 (Aerobic Time) | = -0.07 |
| | 2 (Anaerobic Time) | = -0.355 |
| | 3 (SRT) | = -0.665 |
| Interactions | 12 | = -1.545 |
| | 13 | = 0.565 |
| | 23 | = -0.45 |
| | 123 | = 0.05 |
| Average | | = 1.485 |

Table III.4 (Continued)

Factorial Analysis Day #6

| | | |
|---|---|---|
| Main Effects | 1 (Aerobic Time) | = -0.84 |
| | 2 (Anaerobic Time) | = 0 |
| | 3 (SRT) | = 0.14 |
| Interactions | 12 | = -2.12 |
| | 13 | = -0.53 |
| | 23 | = -0.59 |
| | 123 | = -0.07 |
| Average | | = 2.045 |

Table III.4 (Continued)

**Factorial Analysis** **Day #7**

| | | |
|---|---|---|
| Main Effects | 1 (Aerobic Time) | = 0.64 |
| | 2 (Anaerobic Time) | = -0.41 |
| | 3 (SRT) | = -0.785 |
| Interactions | 12 | = -3.32 |
| | 13 | = 0.135 |
| | 23 | = -0.385 |
| | 123 | = -0.475 |
| Average | | = 2.58 |

Table III.4 (Continued)

**Factorial Analysis Day #9**

| | | |
|---|---|---|
| Main Effects | 1 (Aerobic Time) | = 1.843 |
| | 2 (Anaerobic Time) | = -0.678 |
| | 3 (SRT) | = -0.638 |
| Interactions | 12 | = -0.162 |
| | 13 | = -0.332 |
| | 23 | = 0.658 |
| | 123 | = 0.512 |
| Average | | = 3.019 |

Table III.4 (Continued)

**Factorial Analysis Day #10**

| | | |
|---|---|---|
| Main Effects | 1 (Aerobic Time) | = 0.83 |
| | 2 (Anaerobic Time) | = 0.425 |
| | 3 (SRT) | = -0.68 |
| Interactions | 12 | = -0.86 |
| | 13 | = 0.405 |
| | 23 | = 0.23 |
| | 123 | = -0.125 |
| Average | | = 3.348 |

Table III.4 (Continued)

Factorial Analysis Day #11

| | | |
|---|---|---|
| Main Effects | 1 (Aerobic Time) | = 0.022 |
| | 2 (Anaerobic Time) | = -0.848 |
| | 3 (SRT) | = -0.758 |
| Interactions | 12 | = -2.834 |
| | 13 | = -0.088 |
| | 23 | = 0.302 |
| | 123 | = 1.0225 |
| Average | | = 3.391 |

Table III.4 (Continued)

**Factorial Analysis Day #12**

| | | |
|---|---|---|
| Main Effects | 1 (Aerobic Time) | = 1.26 |
| | 2 (Anaerobic Time) | = -1.095 |
| | 3 (SRT) | = -0.82 |
| Interactions | 12 | = -1.825 |
| | 13 | = -0.40 |
| | 23 | = 0.515 |
| | 123 | = -0.345 |
| Average | | = 2.315 |

## Table III.4 (Continued)

Factorial Analysis Day #13

| | | |
|---|---|---|
| Main Effects | 1 (Aerobic Time) | = 1.41 |
| | 2 (Anaerobic Time) | = -1.325 |
| | 3 (SRT) | = -0.62 |
| Interactions | 12 | = -1.395 |
| | 13 | = -0.85 |
| | 23 | = -0.545 |
| | 123 | = -0.075 |
| Average | | = 2.66 |

## Table III.4 (Continued)

**Factorial Analysis** **Day #14**

| | | |
|---|---|---|
| Main Effects | 1 (Aerobic Time) | = 1.495 |
| | 2 (Anaerobic Time) | = -0.45 |
| | 3 (SRT) | = -0.69 |
| Interactions | 12 | = -1.845 |
| | 13 | = -0.075 |
| | 23 | = -1.63 |
| | 123 | = 0.295 |
| Average | | = 2.25 |

Table III.4 (Continued)

**Factorial Analysis Day #15**

| | | |
|---|---|---|
| Main Effects | 1 (Aerobic Time) | = 0.925 |
| | 2 (Anaerobic Time) | = -1.365 |
| | 3 (SRT) | = -1.205 |
| Interactions | 12 | = -0.16 |
| | 13 | = 0.30 |
| | 23 | = -0.54 |
| | 123 | = -0.515 |
| Average | | = 3.55 |

**Table III.5 Analysis of Variance Tables for Main Effects and Interactions in Biological Phosphorus Removal (Using Same Day Estimates of Error Variance)**

October 11, 1985 (Day 5)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 0.0098 | 1 | 0.0098 | 1.96 | |
| 2 | 0.2520 | 1 | 0.2520 | 50.41 | 90 |
| 3 | 0.8844 | 1 | 0.8844 | 176.89 | 95 |
| 1x2 | 4.7740 | 1 | 4.7740 | 954.81 | 95 |
| 1x3 | 0.6384 | 1 | 0.6384 | 127.69 | 90 |
| 2x3 | 0.4050 | 1 | 0.4050 | 81.00 | 90 |
| Error | 0.0050 | 1 | 0.0050 | | |

Effects used for Error Mean Square Estimation (MSE) : 1x2x3

$MSE = 2x0.05^2 = 0.005$

Table III.5 (Continued)

October 12, 1985 (Day 6)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 1.4112 | 1 | 1.4112 | 7.41 | 90 |
| 2 | - | - | - | - | |
| 3 | 0.0392 | 1 | 0.0392 | 0.21 | |
| 1x2 | 8.9888 | 1 | 8.9888 | 47.19 | 99 |
| 1x3 | - | - | - | - | |
| 2x3 | 0.6962 | 1 | 0.6962 | 3.65 | |
| Error | 0.5716 | 3 | 0.1905 | | |

Effects used for Error Mean Square Estimation (MSE) : 1x2x3, 2, 1x3

$MSE = \frac{1}{3} \times 2 \times (-0.07^2 + 0 + (-0.53)^2) = 0.1905$

Table III.5 (Continued)

October 13, 1985 (Day 7)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 0.8192 | 1 | 0.8192 | 2.98 | - |
| 2 | - | - | - | - | - |
| 3 | 1.2324 | 1 | 1.2324 | 4.49 | - |
| 1x2 | 22.0448 | 1 | 22.0448 | 80.28 | 99 |
| 1x3 | - | - | - | - | - |
| 2x3 | 0.2964 | 1 | 0.2964 | 1.08 | - |
| Error | 0.8239 | 3 | 0.2746 | | |

Effects used for Error Mean Square Estimation (MSE) : 1x2x3, 2, 1x3

$MSE = \frac{1}{3} \times 2 \times (0.135^2 + (-0.41)^2 + + (-0.475)^2 = 0.2746$

### Table III.5 (Continued)

October 15, 1985 (Day 9)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 6.7896 | 1 | 6.7896 | 25.48 | 95 |
| 2 | 0.9180 | 1 | 0.9180 | 3.45 | |
| 3 | 0.8128 | 1 | 0.8128 | 3.05 | |
| 1x2 | - | - | - | - | |
| 1x3 | - | - | - | - | |
| 2x3 | 0.8646 | 1 | 0.8646 | 3.25 | |
| Error | 0.3996 | 3 | 0.2644 | | |

Effects used for Error Mean Square Estimation (MSE) : 1x2x3, 1x2, 1x3

$MSE = \frac{1}{3} \times 2 \times (-0.1625^2 + + (-0.3325)^2 + 0.5125^2) = 0.2644$

**Table III.5 (Continued)**

October 16, 1985 (Day 10)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 1.3778 | 1 | 1.3778 | 8.89 | 90 |
| 2 | 0.3612 | 1 | 0.3612 | 2.33 | |
| 3 | 0.9248 | 1 | 0.9248 | 5.97 | |
| 1x2 | 1.4792 | 1 | 1.4792 | 9.54 | 90 |
| 1x3 | - | - | - | - | |
| 2x3 | - | - | - | - | |
| Error | 0.4651 | 3 | 0.1550 | | |

Effects used for Error Mean Square Estimation (MSE) : 1x2x3, 2x3, 1x3

$MSE = \frac{1}{3} \times 2 \times (-0.125^2 + + (0.230)^2 + 0.405^2) = 0.1550$

Table III.5 (Continued)

October 18, 1985 (Day 12)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 3.1752 | 1 | 3.1752 | 11.38 | 90 |
| 2 | 2.3980 | 1 | 2.3980 | 8.59 | 90 |
| 3 | 1.3448 | 1 | 1.3448 | 4.82 | |
| 1x2 | 6.6616 | 1 | 6.6616 | 23.88 | 95 |
| 1x3 | - | - | - | - | |
| 2x3 | 0.5304 | 1 | 0.5304 | 1.90 | |
| Error | 0.5580 | 2 | 0.2790 | | |

Effects used for Error Mean Square Estimation (MSE) : 1x2x3, 1x3

$MSE = \frac{1}{2} \times 2 \times (-0.345^2 + + (0.40)^2) = 0.2790$

### Table III.5 (Continued)

October 19, 1985 (Day 13)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 3.9762 | 1 | 3.9762 | 13.14 | 90 |
| 2 | 3.5112 | 1 | 3.5112 | 11.60 | 90 |
| 3 | 0.7688 | 1 | 0.7688 | 2.54 | |
| 1x2 | 3.8920 | 1 | 3.8920 | 12.86 | 90 |
| 1x3 | 1.4450 | 1 | 1.4450 | 4.78 | |
| 2x3 | - | - | - | - | |
| Error | 0.6053 | 2 | 0.3026 | | |

Effects used for Error Mean Square Estimation (MSE) : 1x2x3, 2x3

$\text{MSE} = \frac{1}{2} \times 2 \times (-0.075^2 + + (0.545)^2) = 0.3026$

Table III.5 (Continued)

October 20, 1985 (Day 14)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 4.4700 | 1 | 4.4700 | 22.71 | 95 |
| 2 | - | - | - | - | |
| 3 | 0.9522 | 1 | 0.9522 | 4.84 | |
| 1x2 | 6.8080 | 1 | 6.8080 | 34.59 | 99 |
| 1x3 | - | - | - | - | |
| 2x3 | 5.3138 | 1 | 5.3138 | 27.00 | 95 |
| Error | 0.2952 | 3 | 0.1968 | | |

Effects used for Error Mean Square Estimation (MSE) : 1x2x3, 2, 1x3

$$MSE = \frac{1}{3} \times 2 \times (0.295^2 + + (-0.45)^2 + (-0.075)^2) = 0.1968$$

## Table III.5 (Continued)

October 21, 1985 (Day 15)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 1.7112 | 1 | 1.7112 | 6.74 | 90 |
| 2 | 3.7264 | 1 | 3.7264 | 14.68 | 95 |
| 3 | 2.9040 | 1 | 2.9040 | 11.44 | 95 |
| 1x2 | - | - | - | - | |
| 1x3 | - | - | - | - | |
| 2x3 | 0.5822 | 1 | 0.5822 | 2.30 | |
| Error | 0.7616 | 3 | 0.2539 | | |

Effects used for Error Mean Square Estimation (MSE) : 1x2x3, 1x2, 1x3

$$MSE = \frac{1}{3} \times 2 \times (-0.16^2 + + 0.30^2 + (-0.515)^2) = 0.2539$$

Table III.6 Analysis of Variance for Main Effects and Interactions in Biological Phosphorus Removal (Using all 1x2x3 Interactions as a Pooled Estimate of Error Variance)

| Day | 1x2x3 Interactions | Sum of Squares |
|---|---|---|
| 5 | 0.050 | 0.0050 |
| 6 | -0.070 | 0.0098 |
| 7 | -0.475 | 0.4512 |
| 8 | - | |
| 9 | 0.512 | 0.5253 |
| 10 | -0.125 | 0.0312 |
| 11 | - | |
| 12 | -0.345 | 0.2380 |
| 13 | -0.075 | 0.0112 |
| 14 | 0.295 | 0.1740 |
| 15 | -0.515 | 0.5304 |
| | | 1.9761 |

$\text{MSE} = \frac{1}{9} \times 1.9761 = 0.2196$

Table III.6 (Continued)

October 11, 1985 (Day 5)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 0.0098 | 1 | 0.0098 | 0.04 | |
| 2 | 0.2520 | 1 | 0.2520 | 1.15 | |
| 3 | 0.8844 | 1 | 0.8844 | 4.03 | 90 |
| 1x2 | 4.7740 | 1 | 4.7740 | 21.74 | 99 |
| 1x3 | 0.6384 | 1 | 0.6384 | 2.91 | |
| 2x3 | 0.4050 | 1 | 0.4050 | 1.84 | |
| Error | 1.9761 | 9 | 0.2196 | | |

Table III.6 (Continued)

October 12, 1985 (Day 6)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 1.4112 | 1 | 1.4112 | 6.43 | 95 |
| 2 | - | - | - | - | |
| 3 | 0.0392 | 1 | 0.0392 | 0.18 | |
| 1x2 | 8.9888 | 1 | 8.9888 | 40.93 | 99 |
| 1x3 | 0.5618 | 1 | 0.5618 | 2.56 | |
| 2x3 | 0.6962 | 1 | 0.6962 | 3.17 | |
| Error | 1.9761 | 9 | 0.2196 | | |

### Table III.6 (Continued)

October 13, 1985 (Day 7)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 0.8192 | 1 | 0.8192 | 3.73 | 90 |
| 2 | 0.3362 | 1 | 0.3362 | 1.53 | |
| 3 | 1.2324 | 1 | 1.2324 | 5.61 | 95 |
| 1x2 | 22.0448 | 1 | 22.0448 | 100.39 | 99 |
| 1x3 | 0.0364 | 1 | 0.0364 | 0.17 | |
| 2x3 | 0.2964 | 1 | 0.2964 | 1.35 | |
| Error | 1.9761 | 9 | 1.9761 | | |

Table III.6 (Continued)

October 15, 1985 (Day 9)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 6.7896 | 1 | 6.7896 | 30.92 | 99 |
| 2 | 0.9180 | 1 | 0.9180 | 4.18 | 90 |
| 3 | 0.8128 | 1 | 0.8128 | 3.70 | 90 |
| 1x2 | 0.0528 | 1 | 0.0528 | 0.24 | |
| 1x3 | 0.2211 | 1 | 0.2211 | 1.01 | |
| 2x3 | 0.8646 | 1 | 0.8646 | 3.94 | 90 |
| Error | 1.9761 | 9 | 1.9761 | | |

## Table III.6 (Continued)

October 16, 1985 (Day 10)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 1.3778 | 1 | 1.3778 | 6.27 | 95 |
| 2 | 0.3612 | 1 | 0.3612 | 1.64 | |
| 3 | 0.9248 | 1 | 0.9248 | 4.21 | 90 |
| 1x2 | 1.4792 | 1 | 1.4792 | 6.74 | 95 |
| 1x3 | 0.3280 | 1 | 0.3280 | 1.49 | |
| 2x3 | 0.1058 | 1 | 0.1058 | 0.48 | |
| Error | 1.9761 | 9 | 0.2196 | | |

Table III.6 (Continued)

October 18, 1985 (Day 12)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 3.1752 | 1 | 3.1752 | 14.46 | 99 |
| 2 | 2.3980 | 1 | 2.3980 | 10.92 | 99 |
| 3 | 1.3448 | 1 | 1.3448 | 6.12 | 95 |
| 1x2 | 6.6616 | 1 | 6.6616 | 30.33 | 99 |
| 1x3 | 0.3200 | 1 | 0.3200 | 1.46 | |
| 2x3 | 0.5304 | 1 | 0.5304 | 2.42 | |
| Error | 1.9761 | 9 | 0.2196 | | |

### Table III.6 (Continued)

October 19, 1985 (Day 13)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 3.9762 | 1 | 3.9762 | 18.44 | 99 |
| 2 | 3.5112 | 1 | 3.5112 | 15.99 | 99 |
| 3 | 0.7688 | 1 | 0.7688 | 3.50 | 90 |
| 1x2 | 3.8920 | 1 | 3.8920 | 17.72 | 99 |
| 1x3 | 1.4450 | 1 | 1.4450 | 6.58 | 95 |
| 2x3 | 0.5940 | 1 | 0.5940 | 2.71 | |
| Error | 1.9761 | 9 | 0.2196 | | |

Table III.6 (Continued)

October 20, 1985 (Day 14)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 4.4700 | 1 | 4.4700 | 20.36 | 99 |
| 2 | 0.4050 | 1 | 0.4050 | 1.84 | |
| 3 | 0.9522 | 1 | 0.9522 | 4.34 | 90 |
| 1x2 | 6.8080 | 1 | 6.8080 | 31.00 | 99 |
| 1x3 | 0.0112 | 1 | 0.0112 | 0.05 | |
| 2x3 | 5.3138 | 1 | 5.3138 | 24.20 | 99 |
| Error | 1.9761 | 9 | 1.9761 | | |

### Table III.6 (Continued)

October 21, 1985 (Day 15)

| Source | Sum of Squares | Degrees of Freedom | Mean Square | F-Ratio | Signif. Level, % |
|---|---|---|---|---|---|
| 1 | 1.7112 | 1 | 1.7112 | 7.79 | 95 |
| 2 | 3.7264 | 1 | 3.7264 | 16.97 | 99 |
| 3 | 2.9040 | 1 | 2.9040 | 13.22 | 99 |
| 1x2 | 0.0512 | 1 | 0.0512 | 0.23 | |
| 1x3 | 0.1800 | 1 | 0.1800 | 0.82 | |
| 2x3 | 0.5822 | 1 | 0.5822 | 2.66 | |
| Error | 1.9761 | 9 | 0.2196 | | |

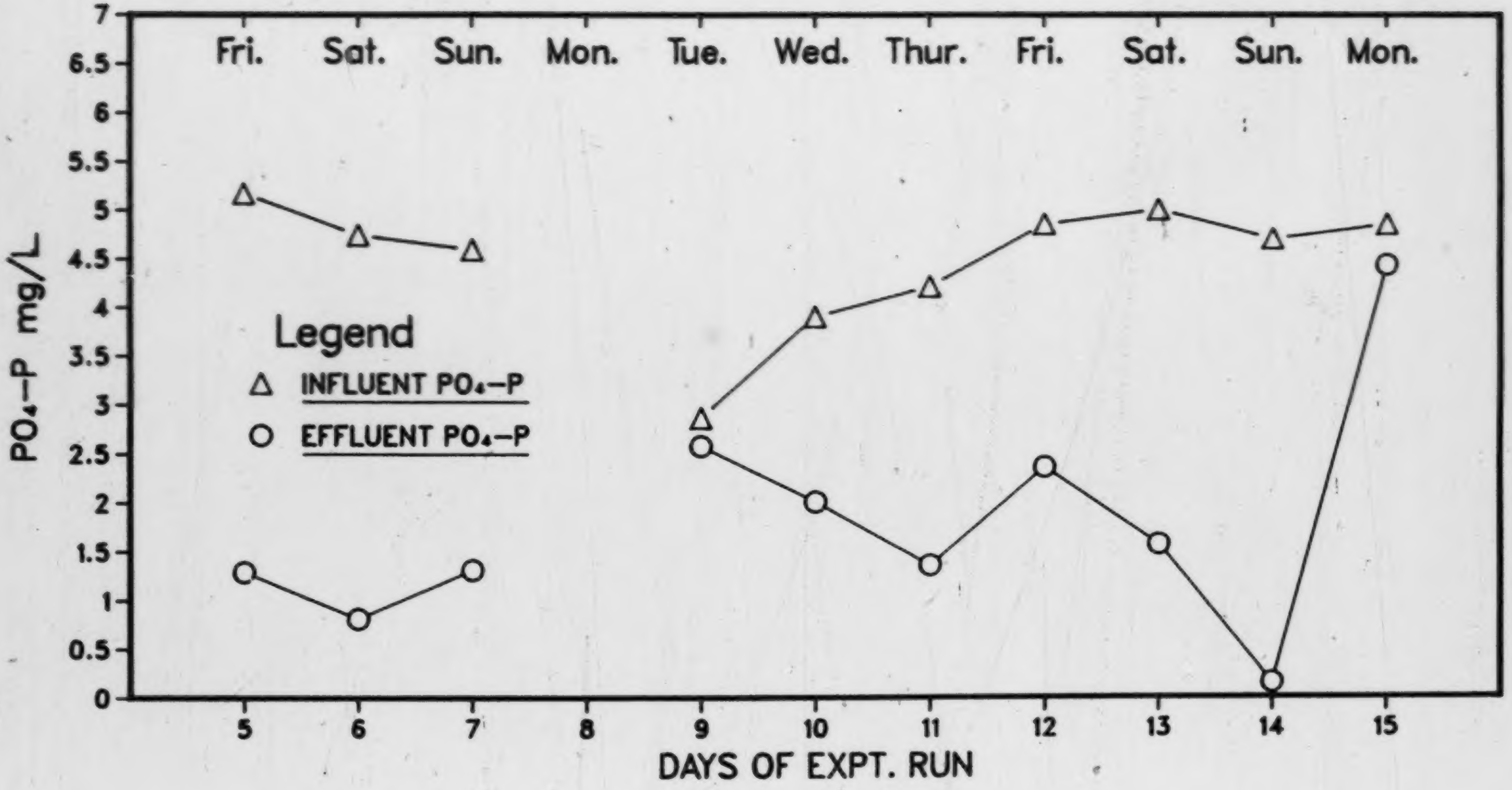


Figure III.1 Influent and Effluent $PO_4$-P Concentrations For Reactor Number one Throughout the Sampling Period.

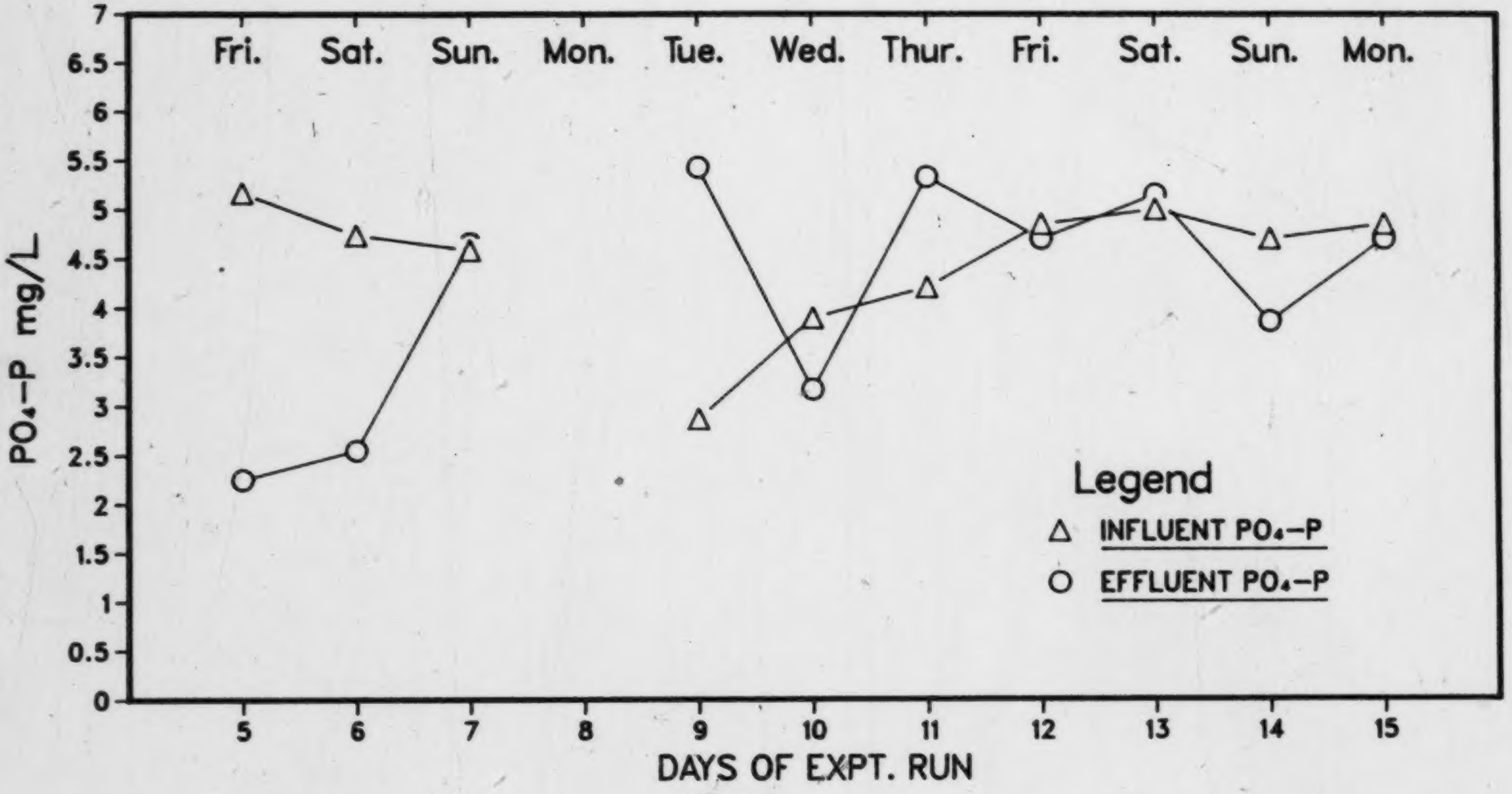


Figure III.2 Influent and Effluent $PO_4$-P Concentrations For Reactor Number two Throughout the Sampling Period.

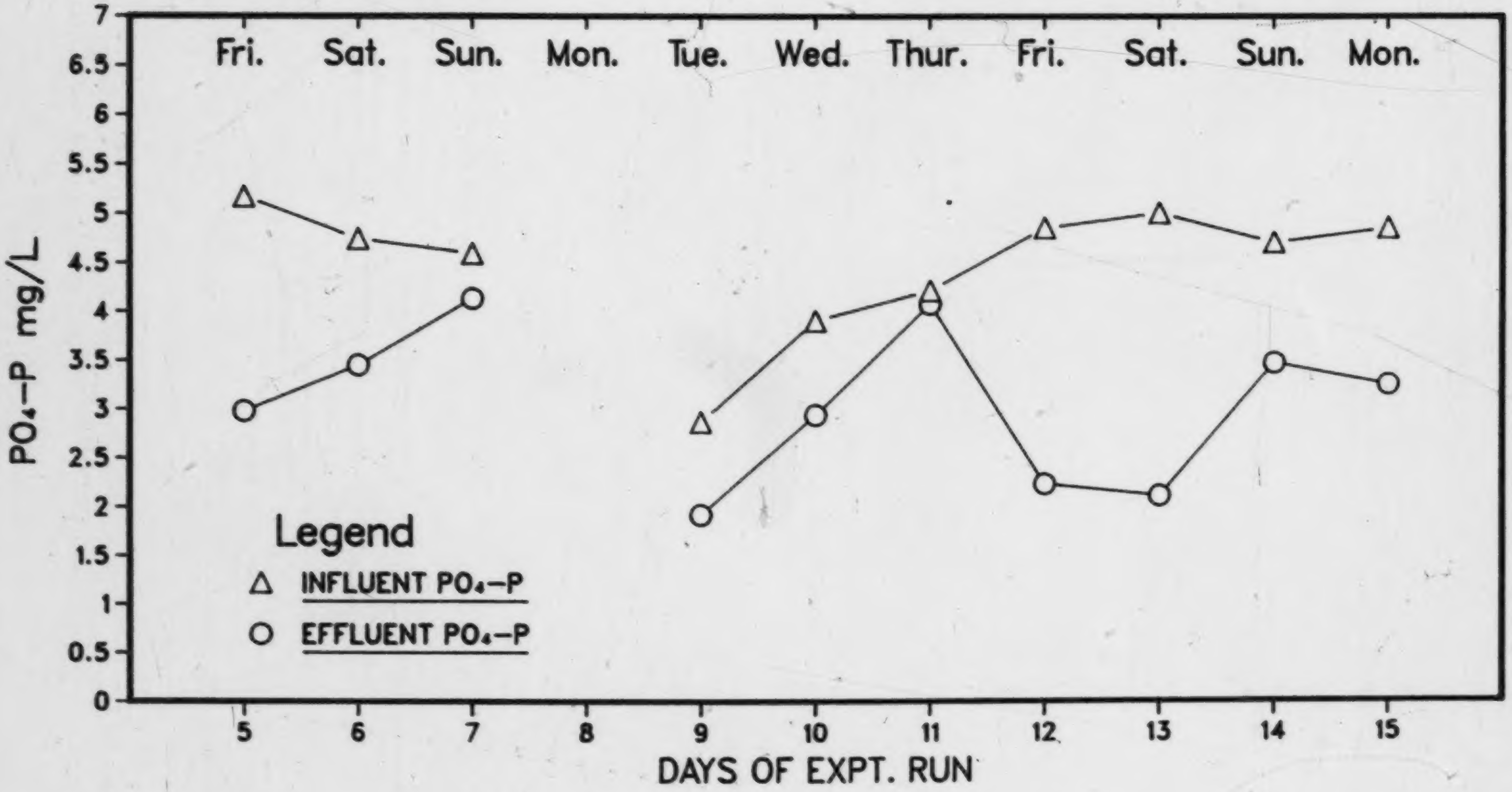


Figure III.3 Influent and Effluent $PO_4$-P Concentrations For Reactor Number three Throughout the Sampling Period.

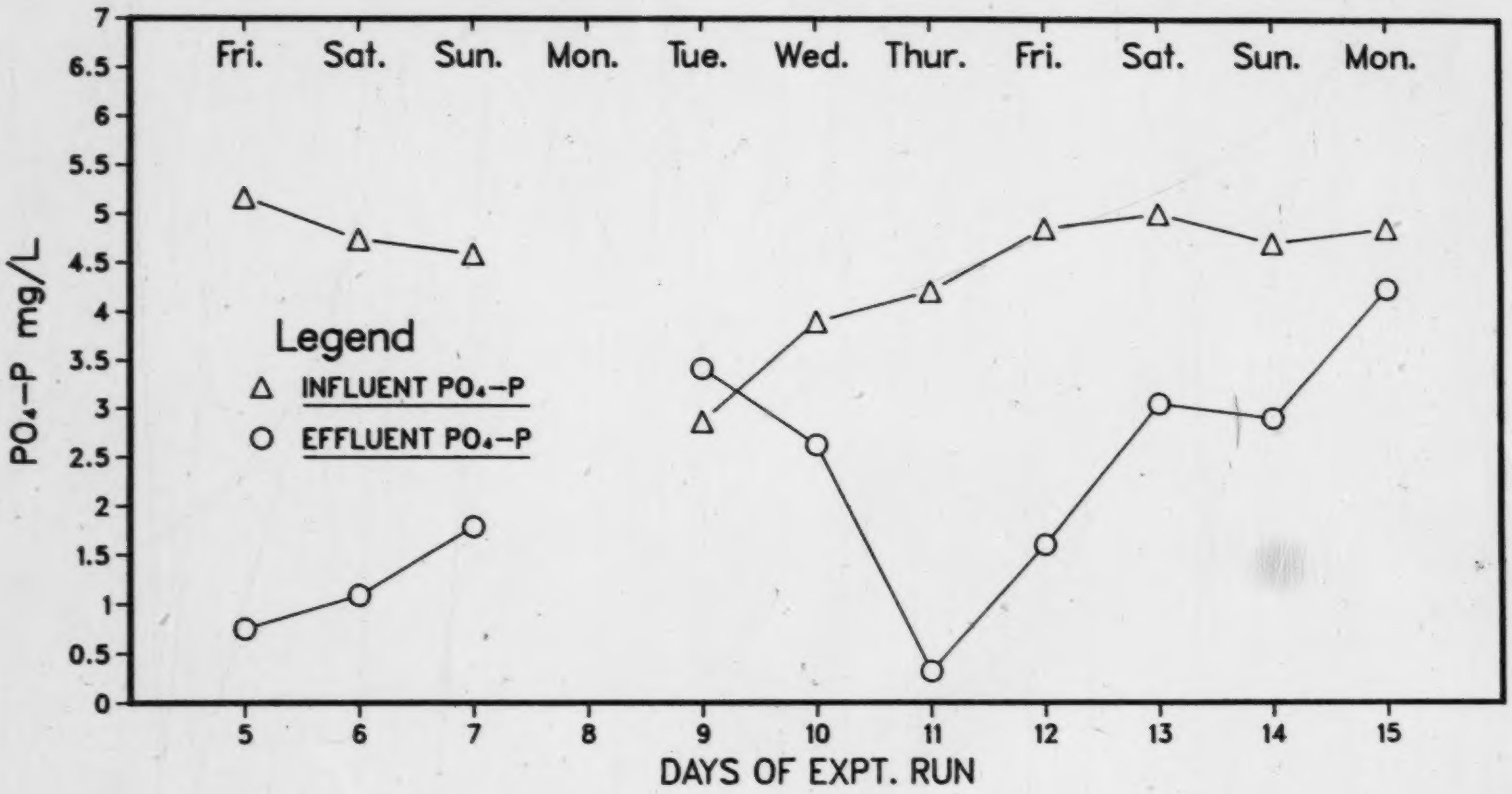


Figure III.4 Influent and Effluent $PO_4$-P Concentrations For Reactor Number four Throughout the Sampling Period.

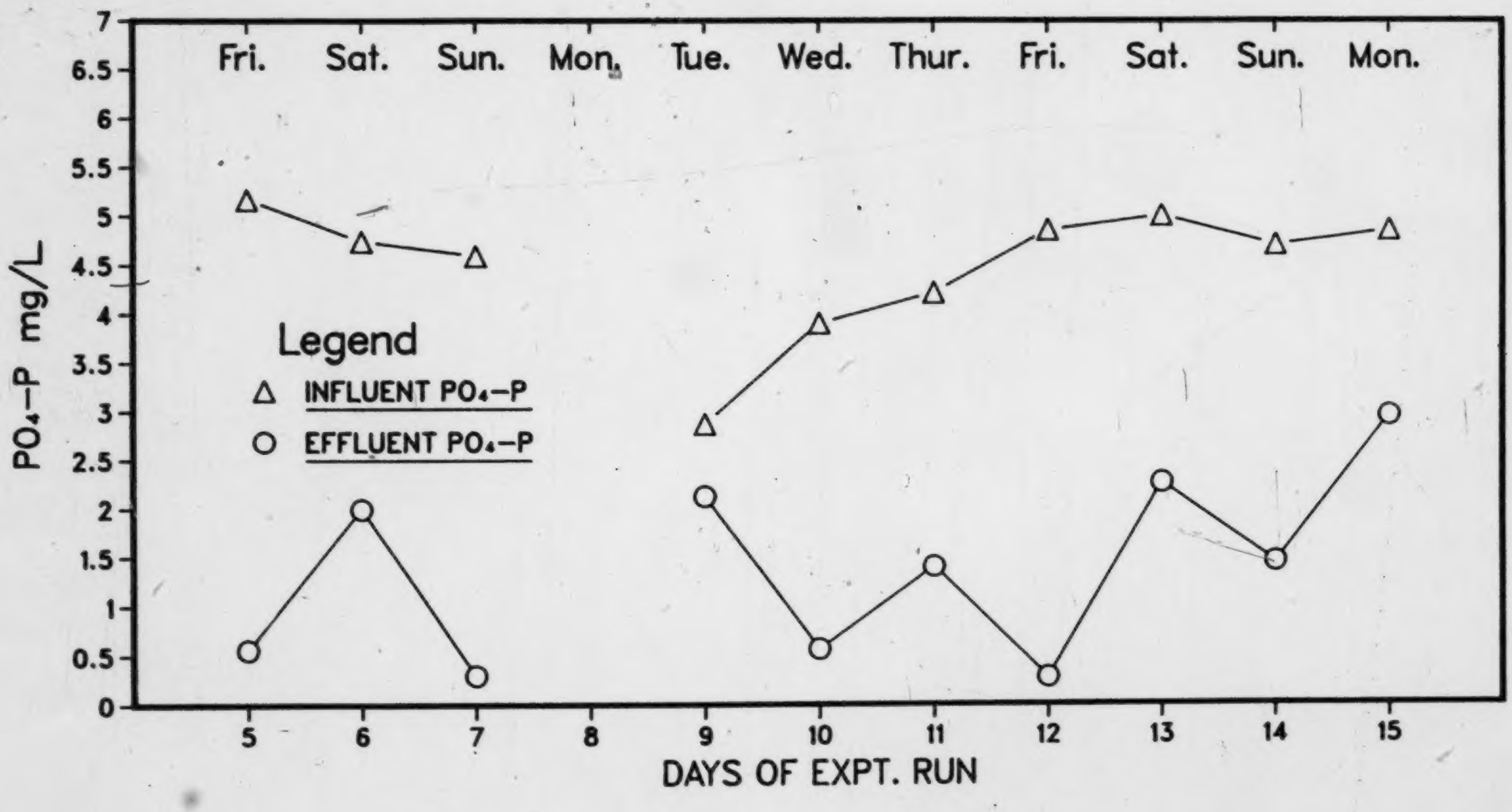


Figure III.5 Influent and Effluent $PO_4$-P Concentrations For Reactor Number five Throughout the Sampling Period.

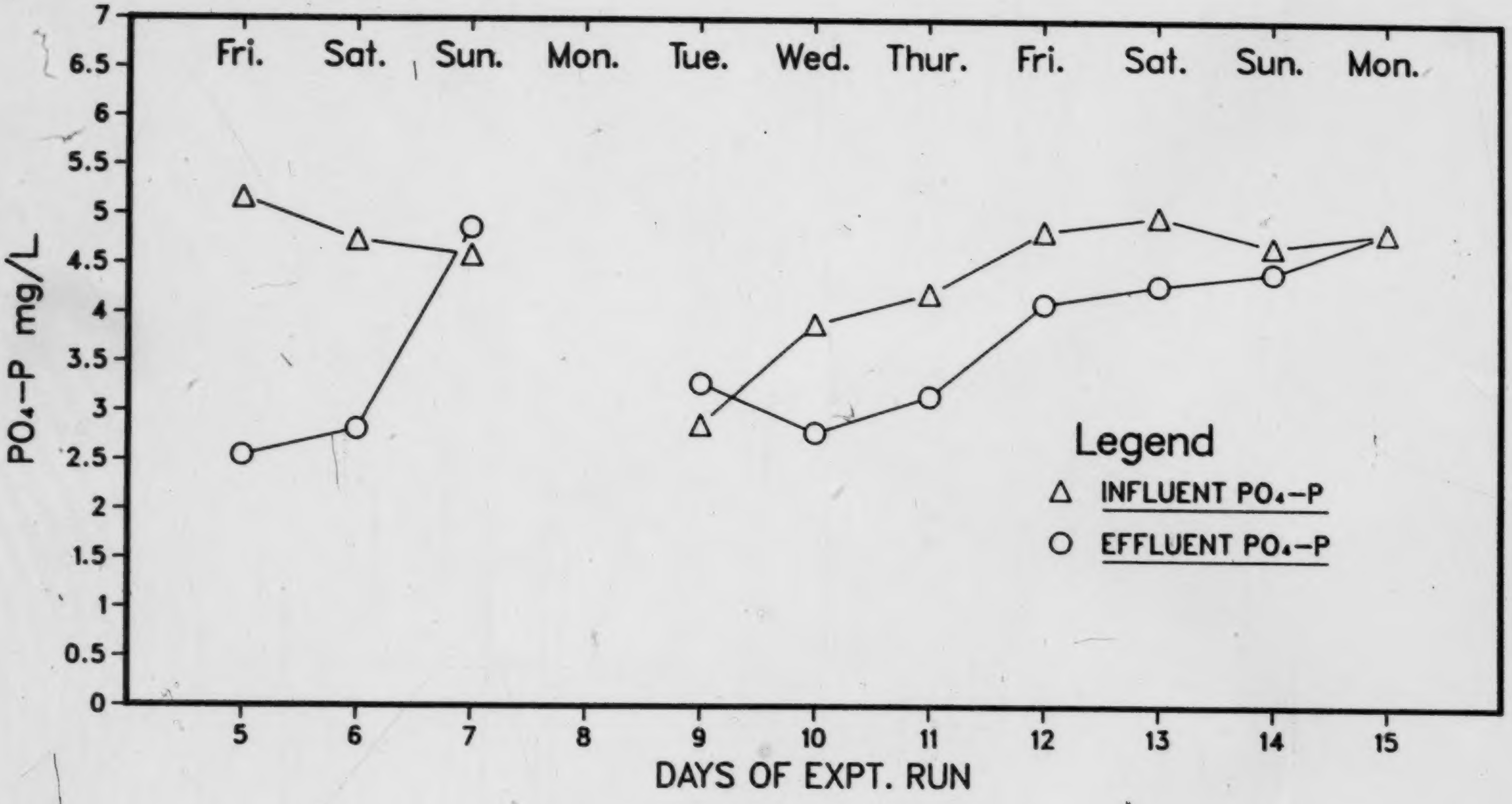


Figure III.6 Influent and Effluent $PO_4$-P Concentrations For Reactor Number six Throughout the Sampling Period.

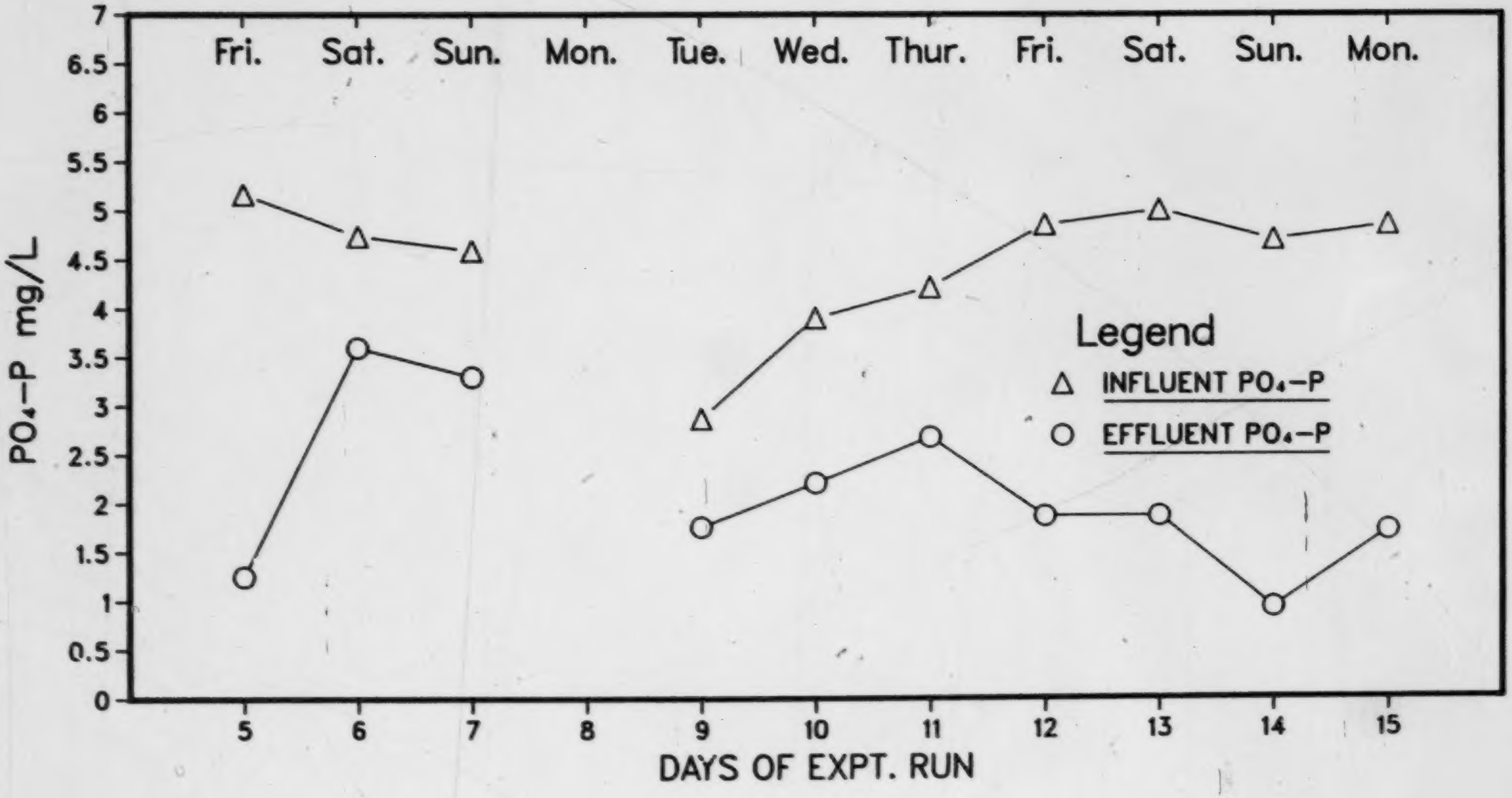


Figure III.7 Influent and Effluent $PO_4$-P Concentrations For Reactor Number seven Throughout the Sampling Period.

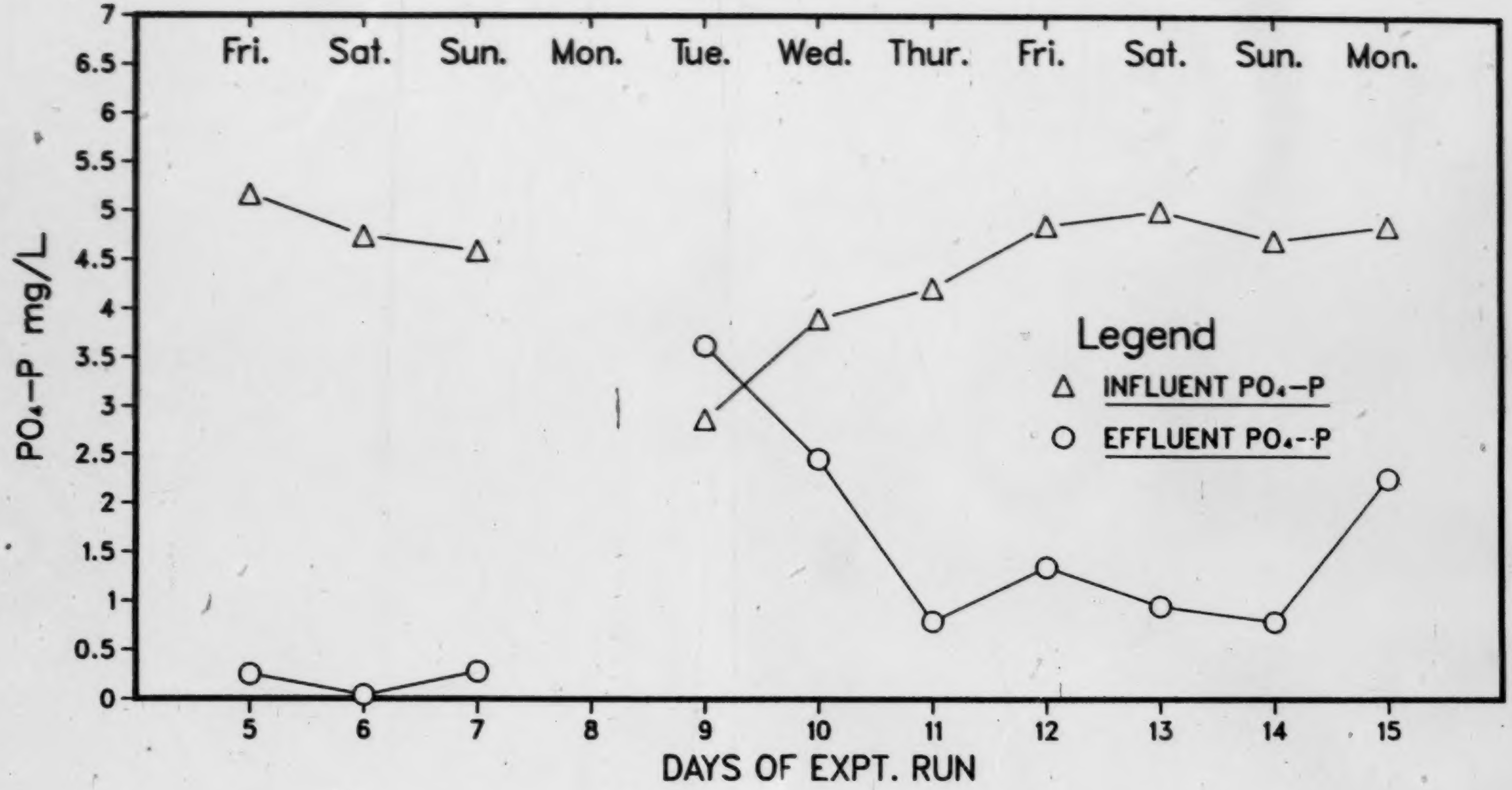


Figure III.8 Influent and Effluent $PO_4$-P Concentrations For Reactor Number eight Throughout the Sampling Period.

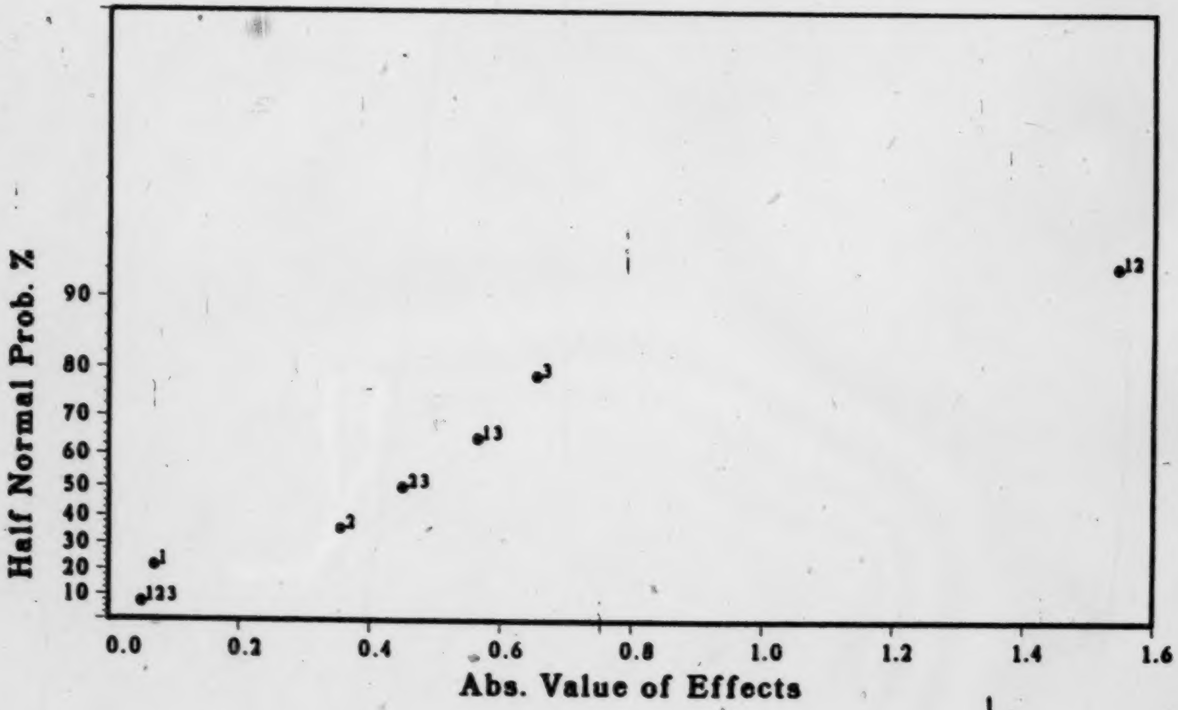


Figure III.9 Half-Normal Probability Plot of $PO_4$-P Removal Effects (Day 5).

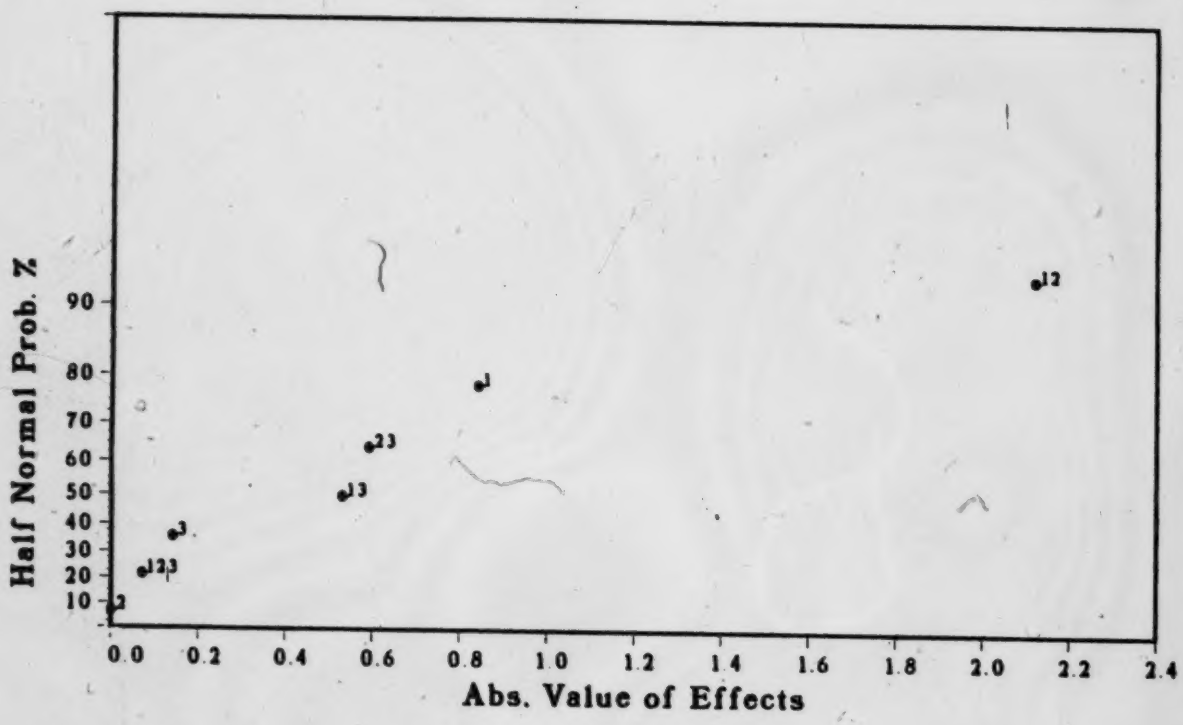


Figure III.10 Half-Normal Probability Plot of $PO_4$-P Removal Effects (Day 6).

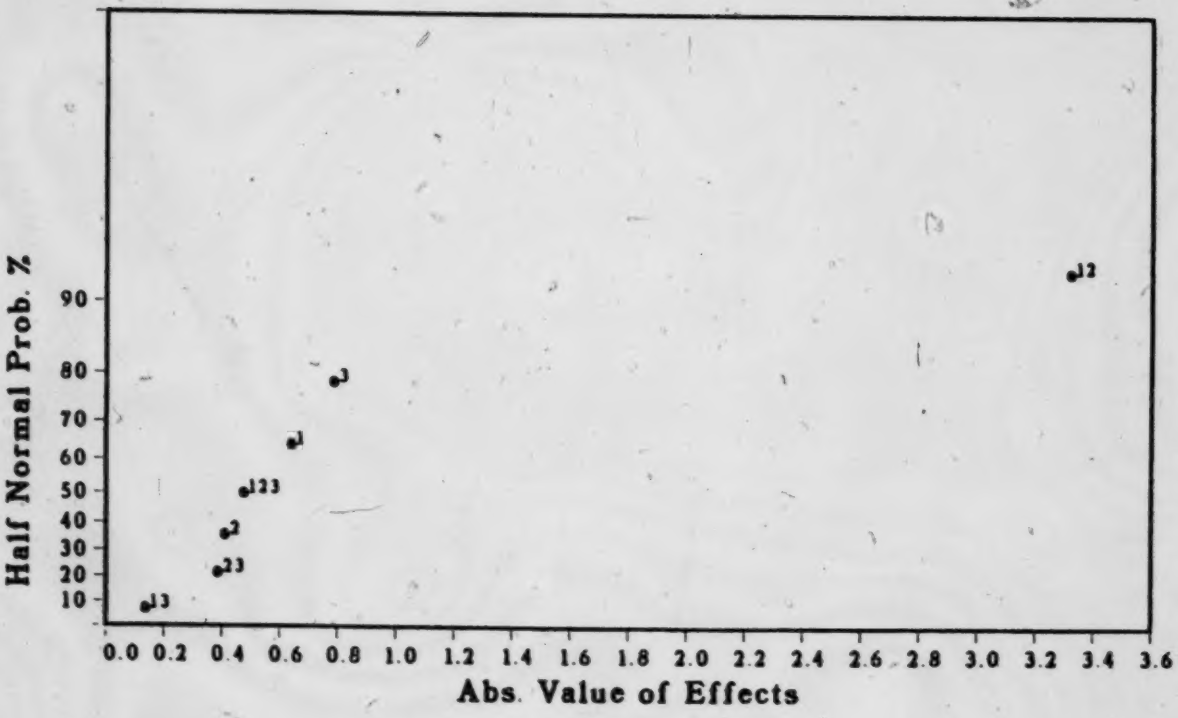


Figure III.11 Half-Normal Probability Plot of $PO_4$-P Removal Effects (Day 7).

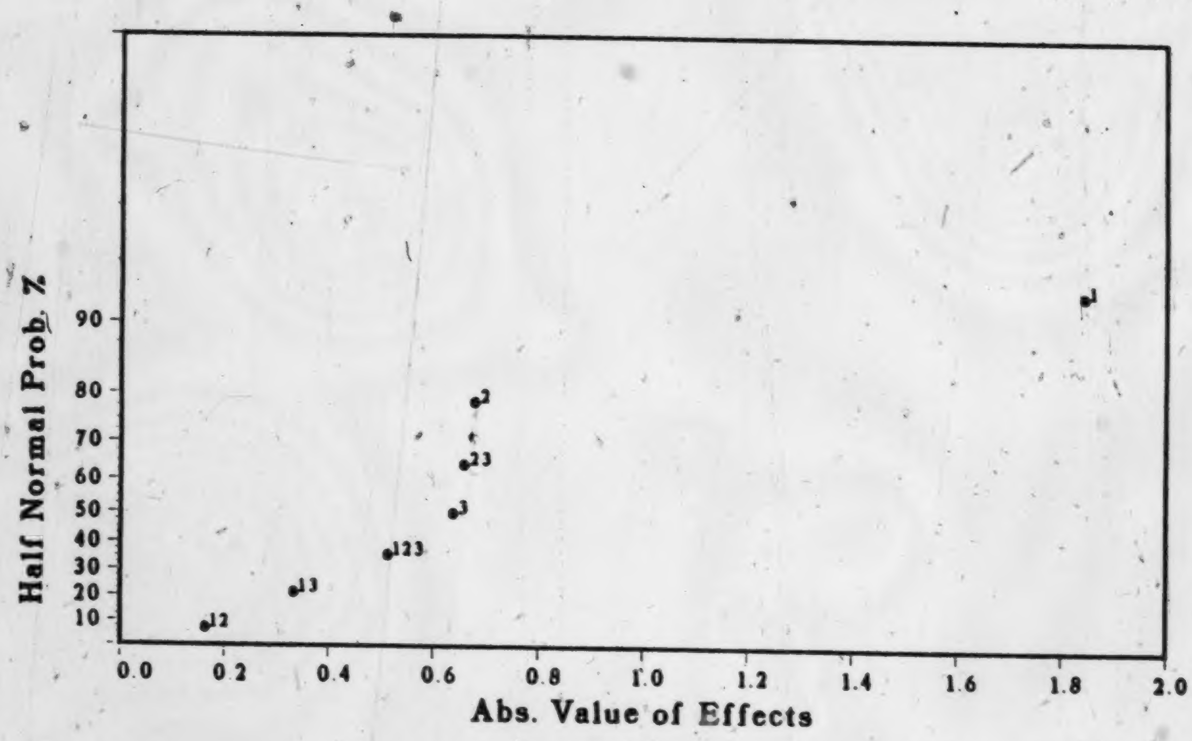


Figure III.12 Half-Normal Probability Plot of $PO_4$-P Removal Effects (Day 9).

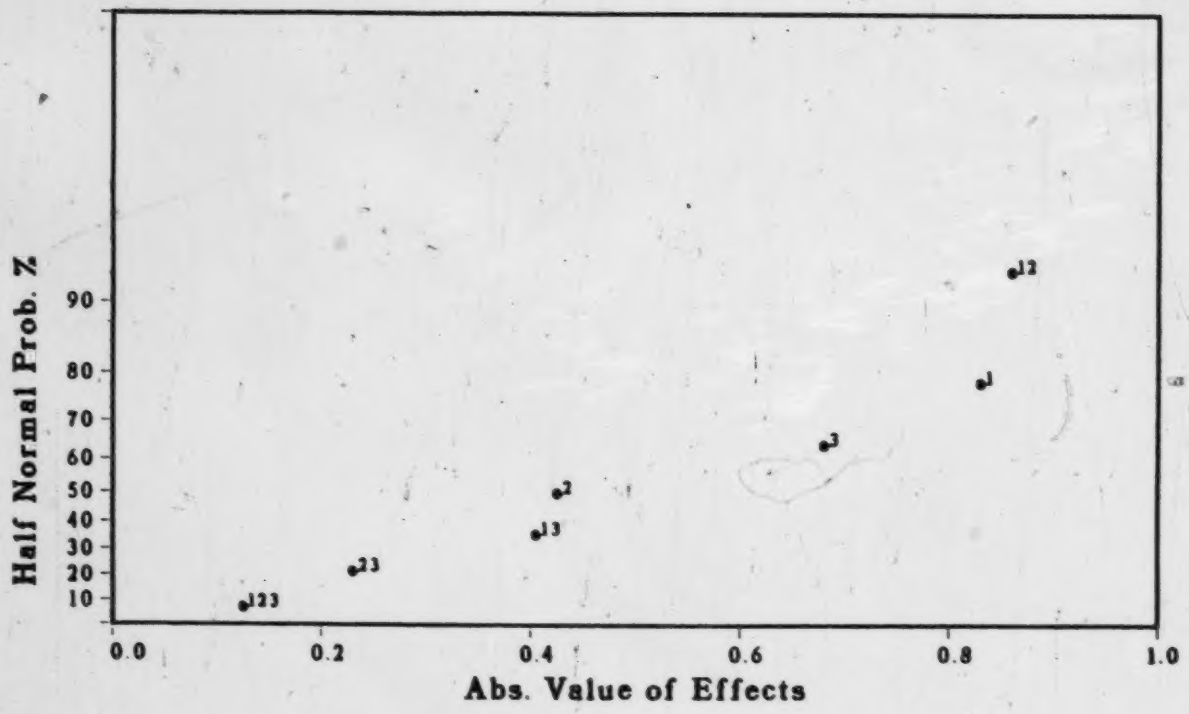


Figure III.13 Half-Normal Probability Plot of PO$_4$-P Removal Effects (Day 10).

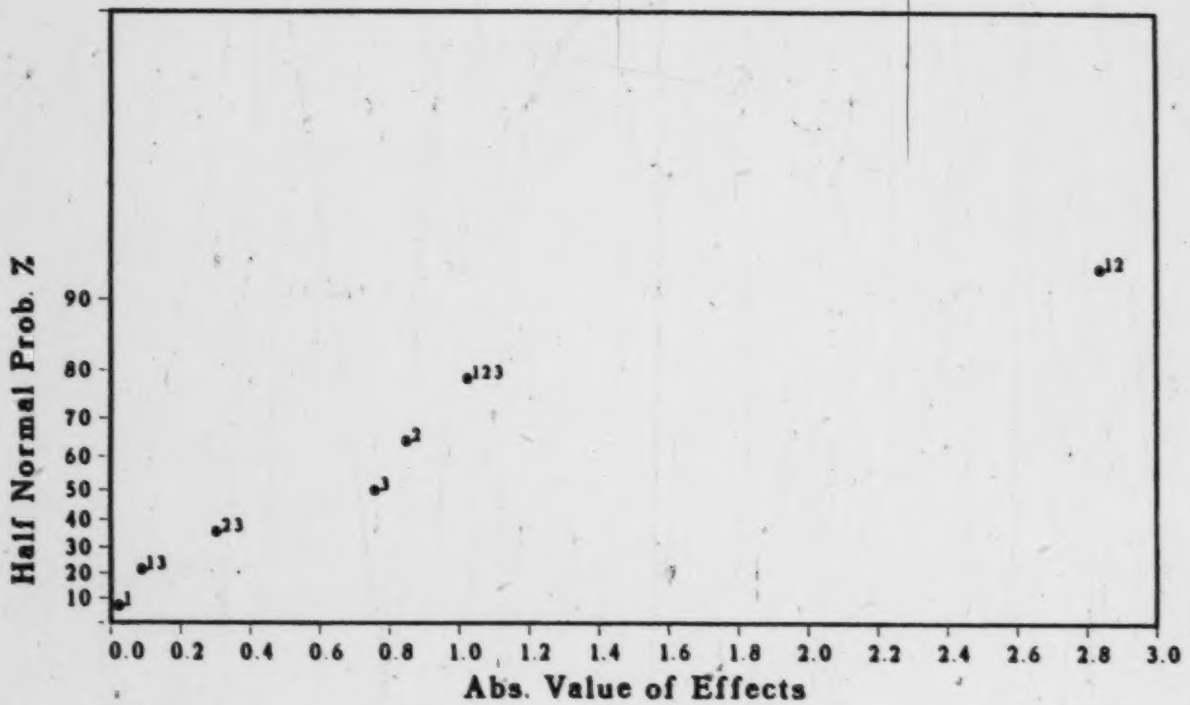


Figure III.14 Half-Normal Probability Plot of $PO_4$-P Removal Effects (Day 11).

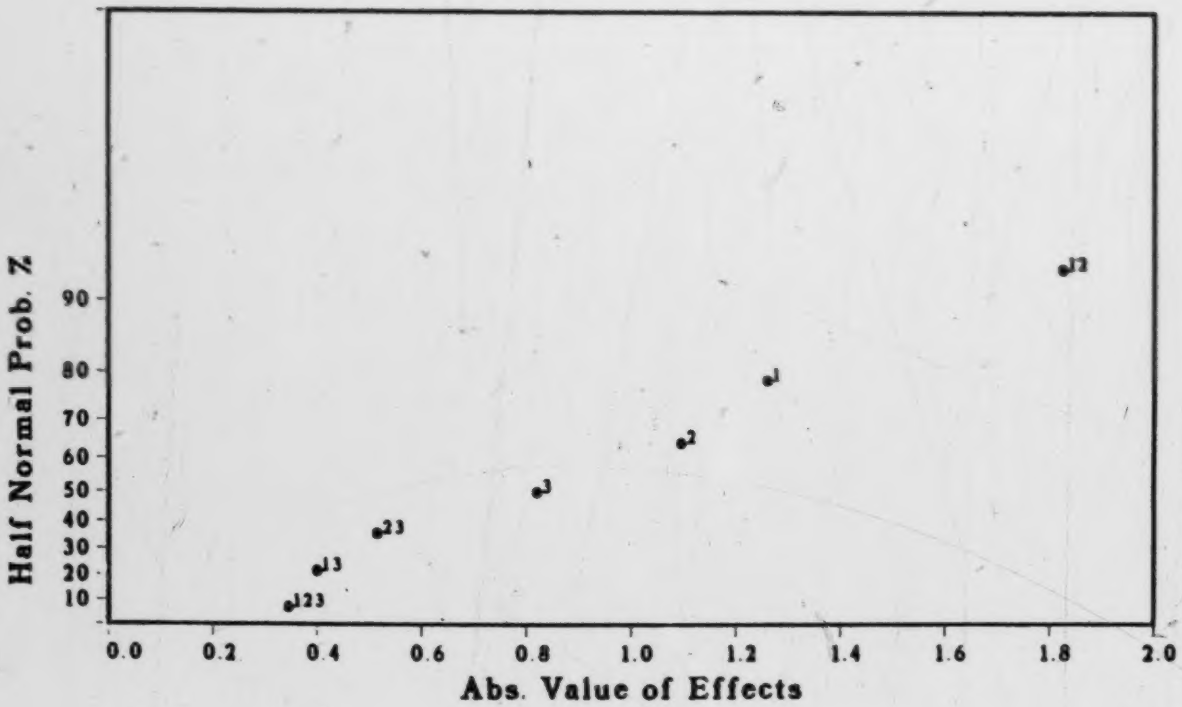


Figure III.15 Half-Normal Probability Plot of $PO_4$-P Removal Effects (Day 12).

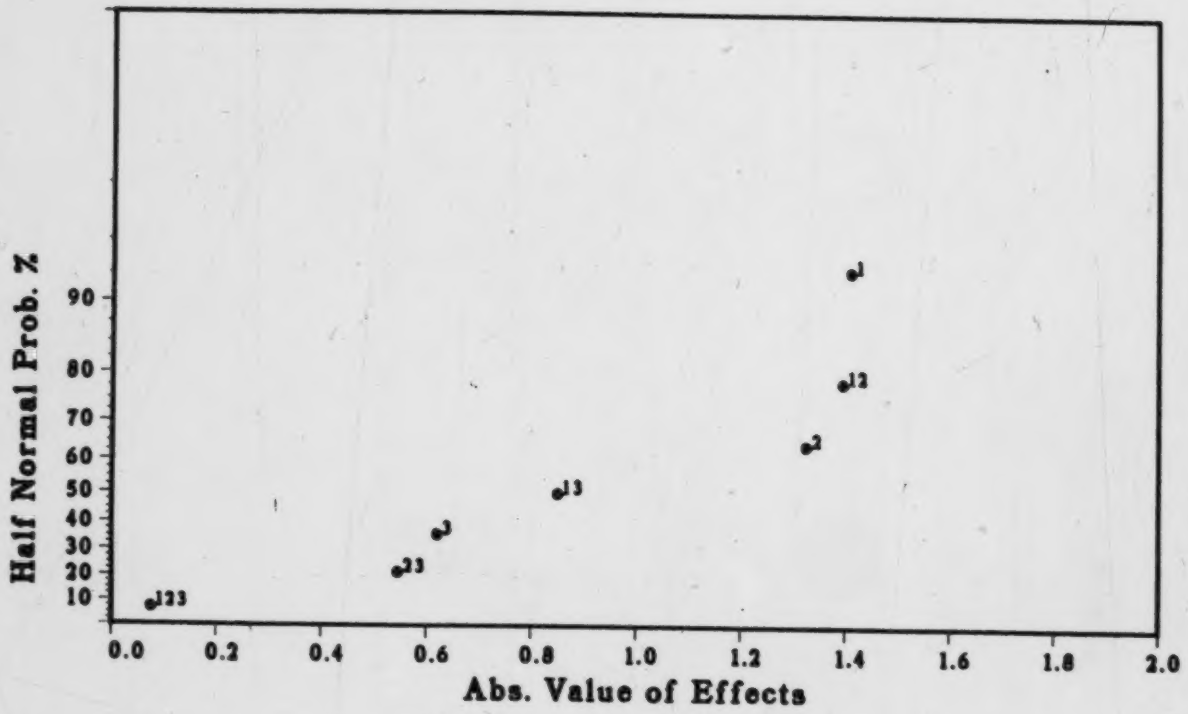


Figure III.16 Half-Normal Probability Plot of $PO_4$-P Removal Effects (Day 13).

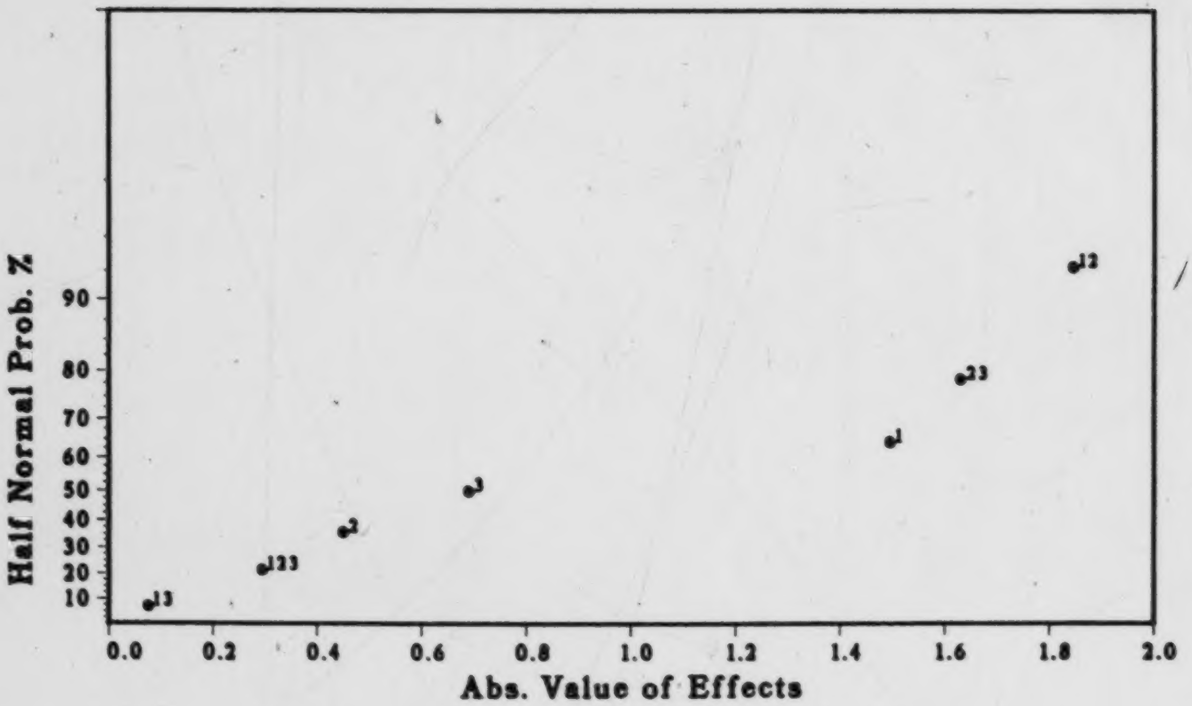


Figure III.17 Half-Normal Probability Plot of $PO_4$-P Removal Effects (Day 14).

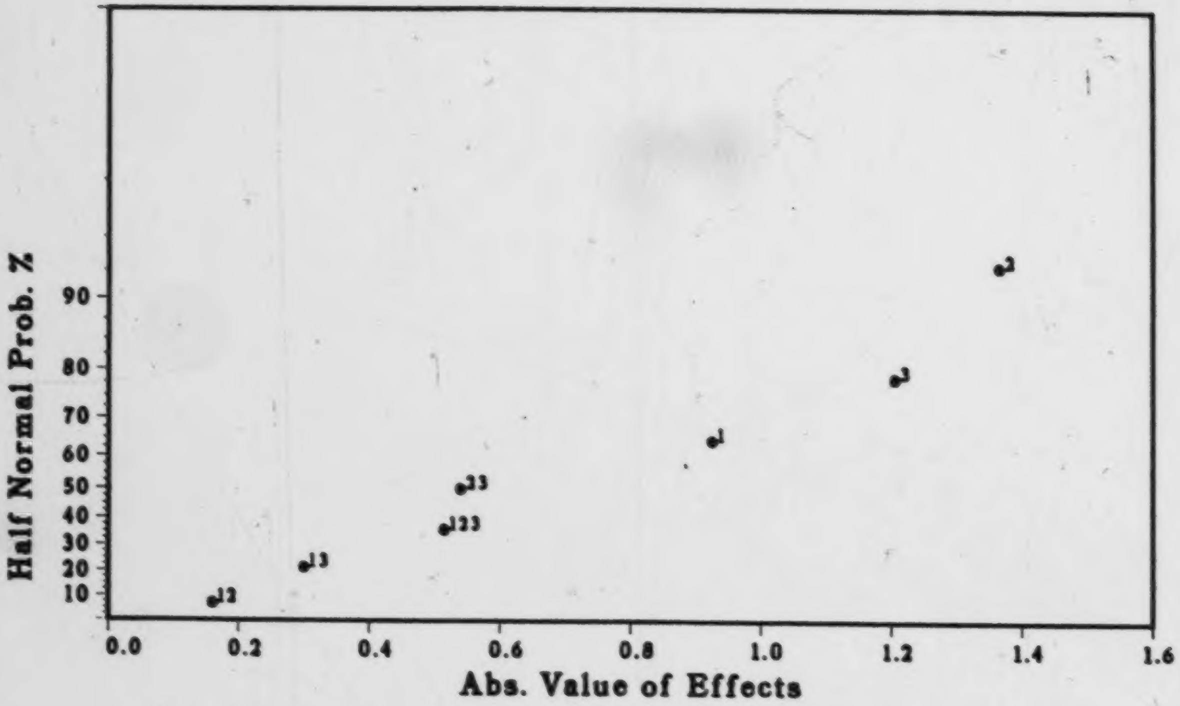


Figure III.18 Half-Normal Probability Plot of $PO_4$-P Removal Effects (Day 15).

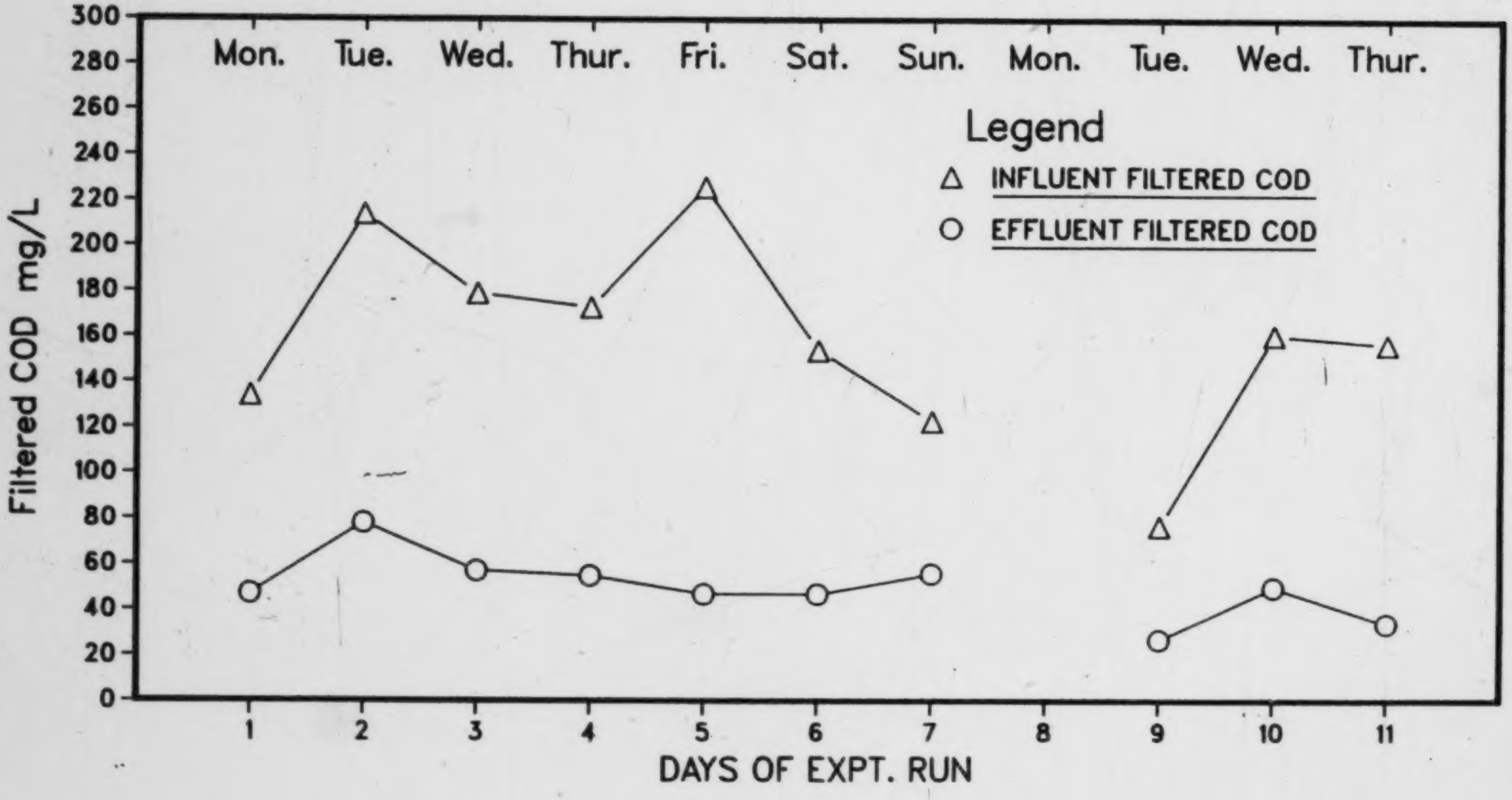


Figure III.19 Influent and Effluent Filtered COD concentrations For Reactor Number One Throughout the Sampling Period.

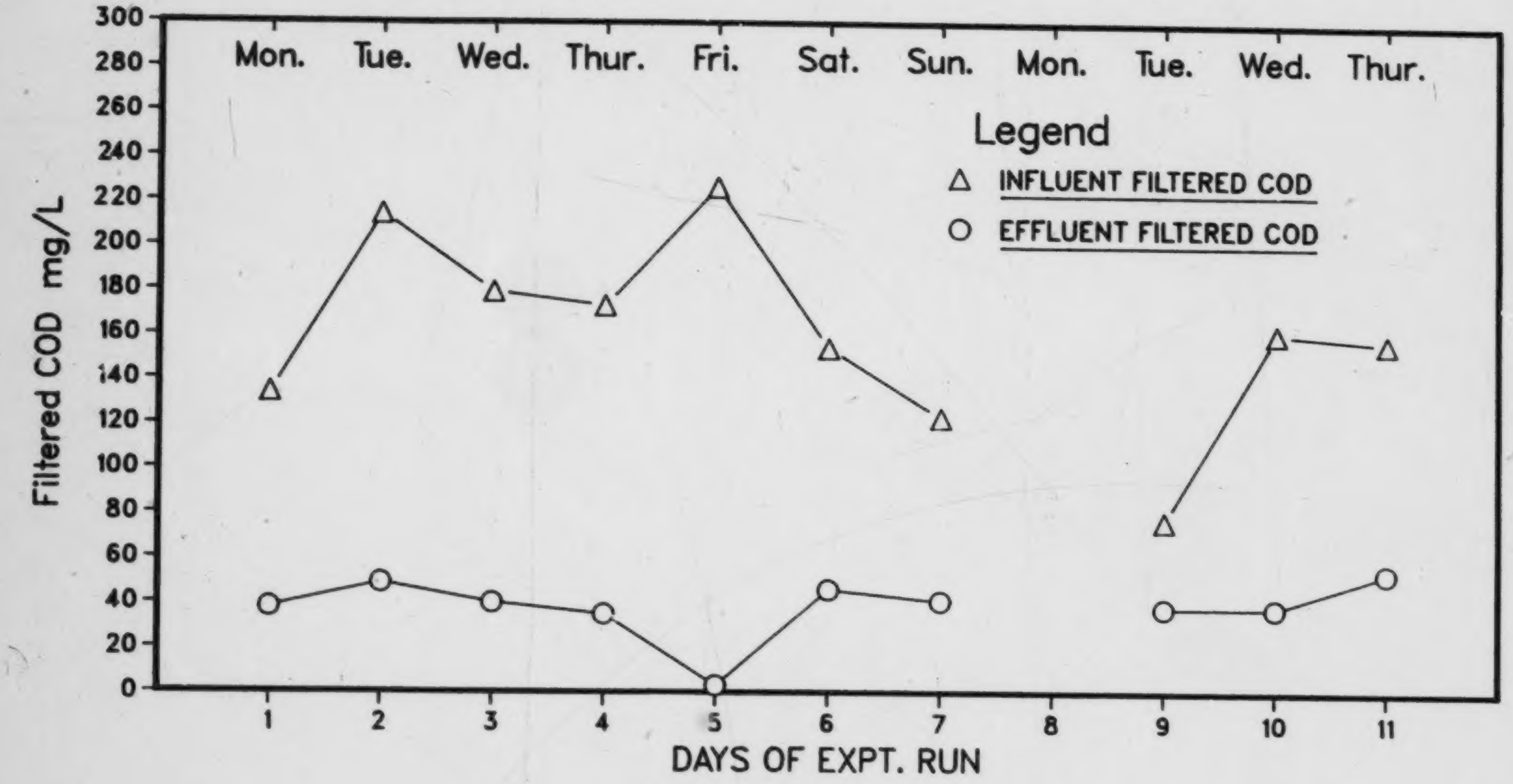


Figure III.20 Influent and Effluent Filtered COD concentrations For Reactor Number Two Throughout the Sampling Period.

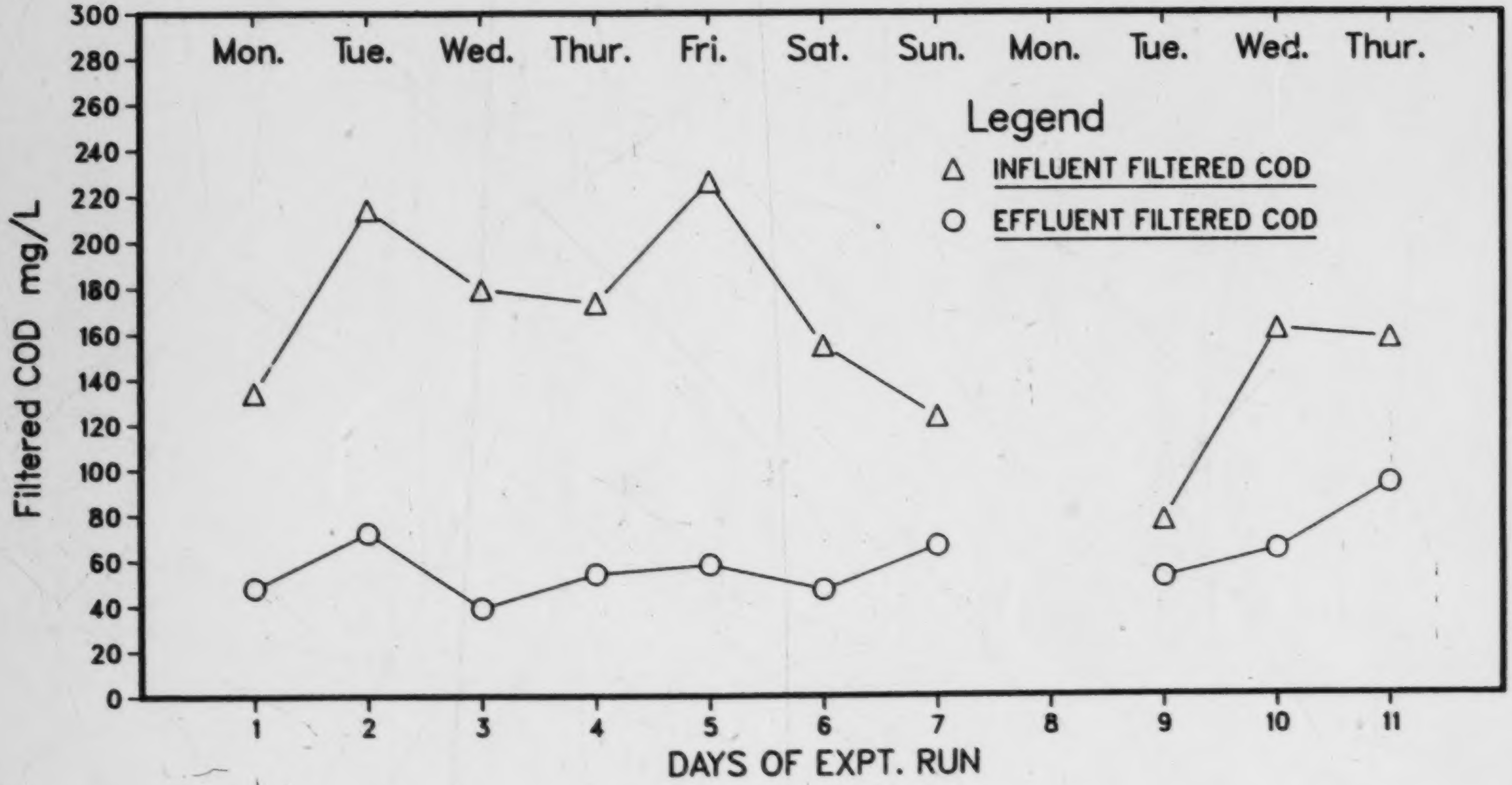


Figure III.21 Influent and Effluent Filtered COD concentrations For Reactor Number Three Throughout the Sampling Period.

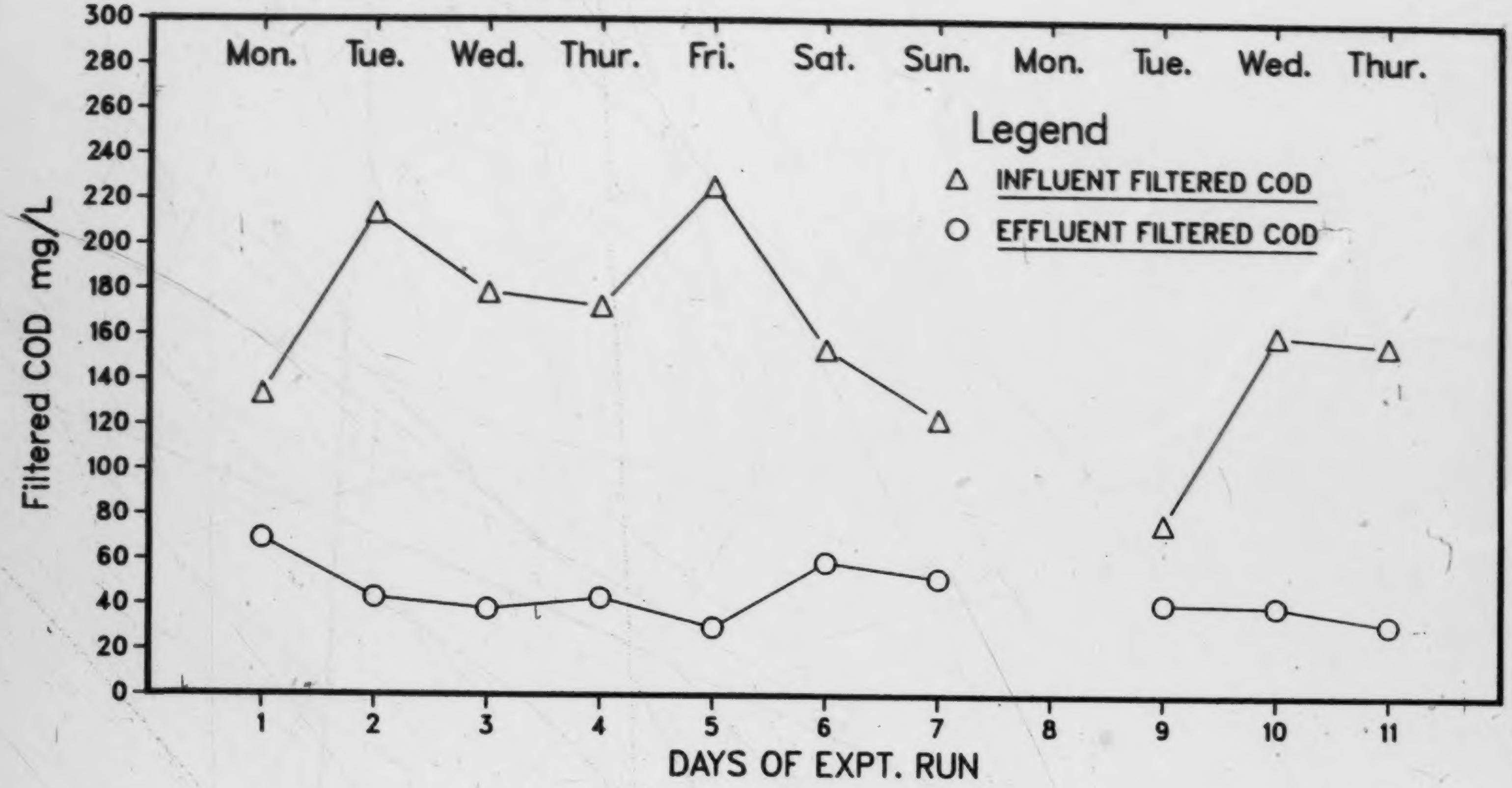


Figure III.22 Influent and Effluent Filtered COD concentrations For Reactor Number Four Throughout the Sampling Period.

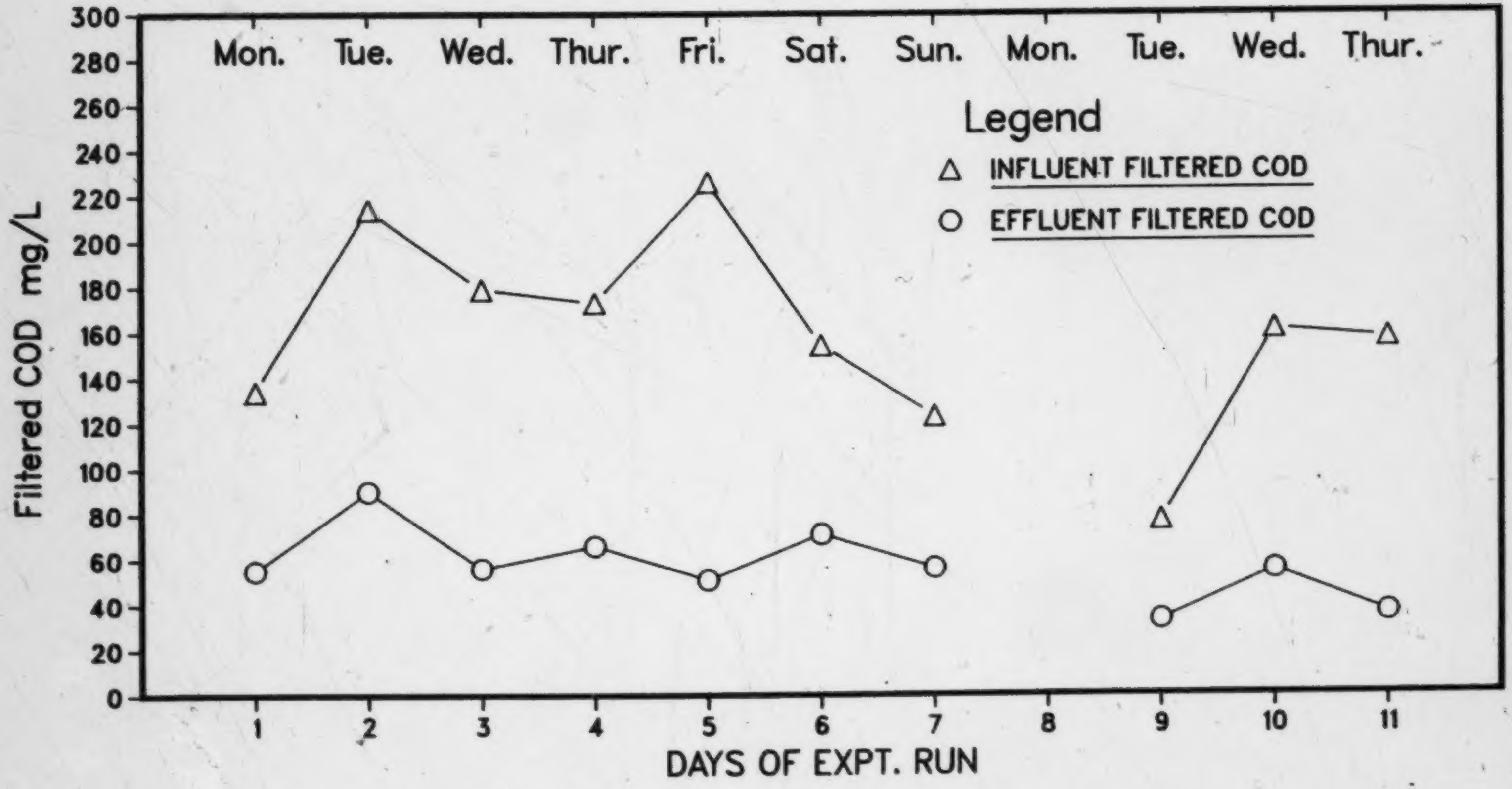


Figure III.23 Influent and Effluent Filtered COD concentrations For Reactor Number Five Throughout the Sampling Period.

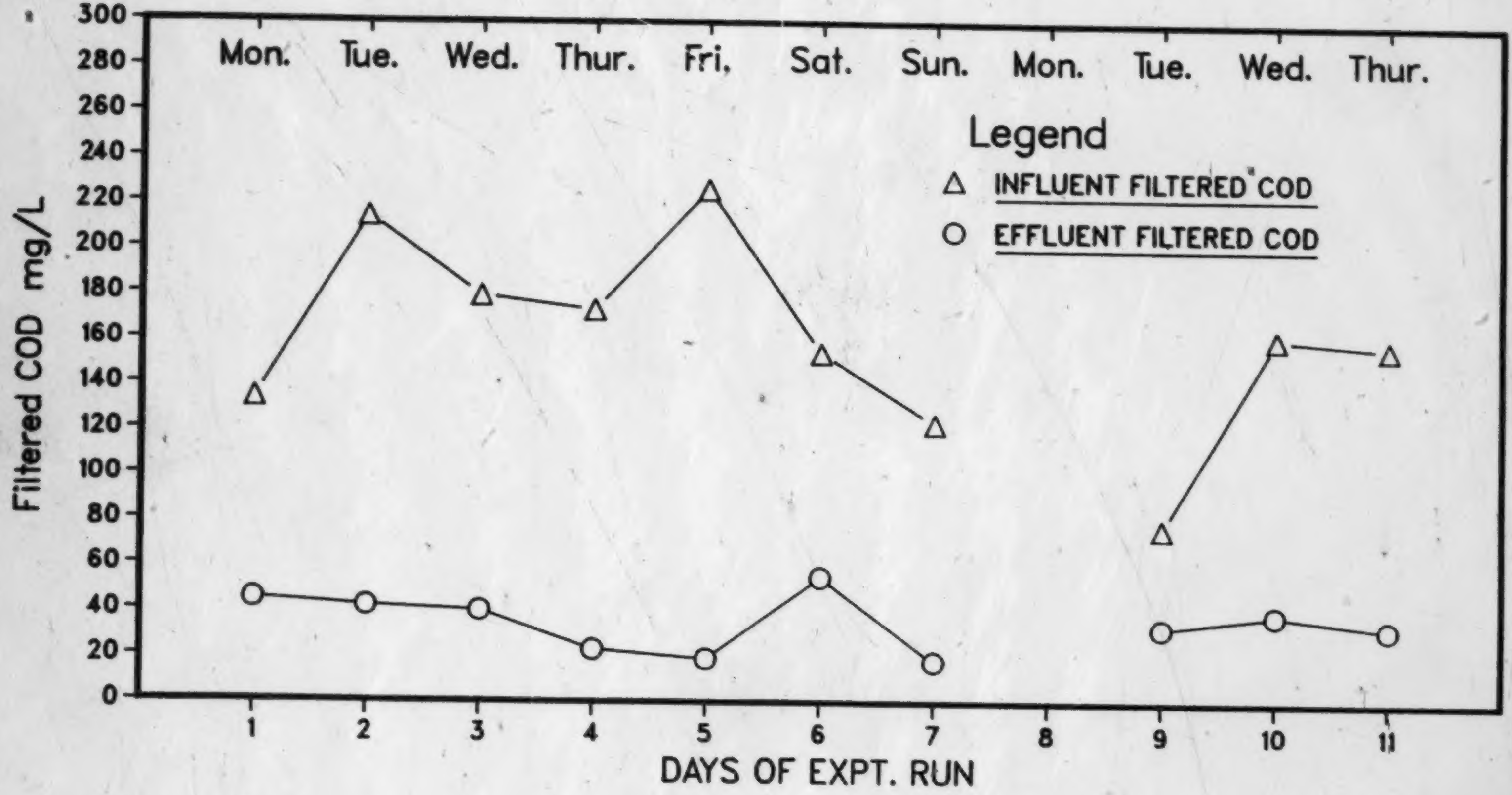


Figure III.24 Influent and Effluent Filtered COD concentrations For Reactor Number Six Throughout the Sampling Period.

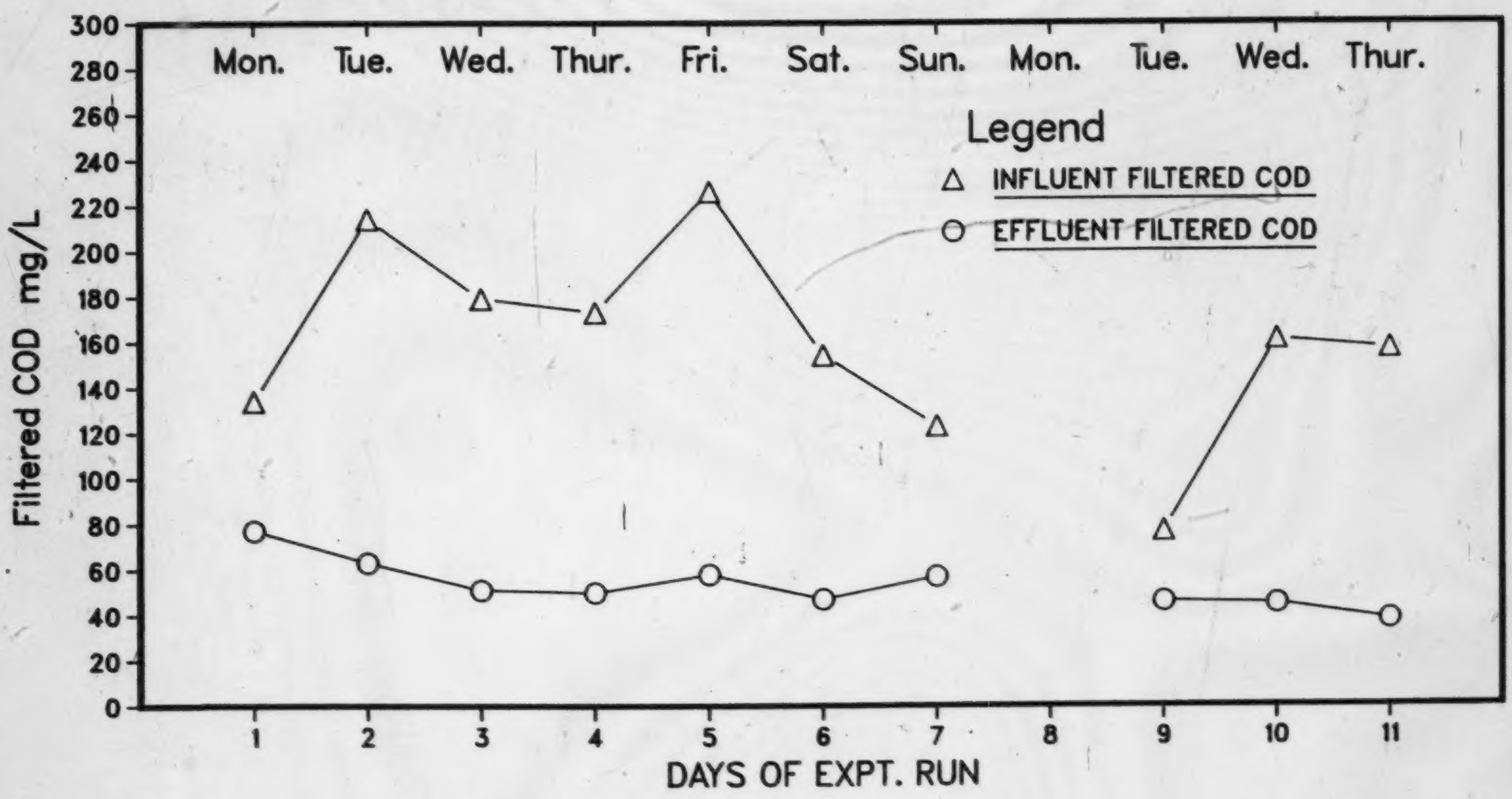


Figure III.25 Influent and Effluent Filtered COD concentrations For Reactor Number Seven Throughout the Sampling Period.

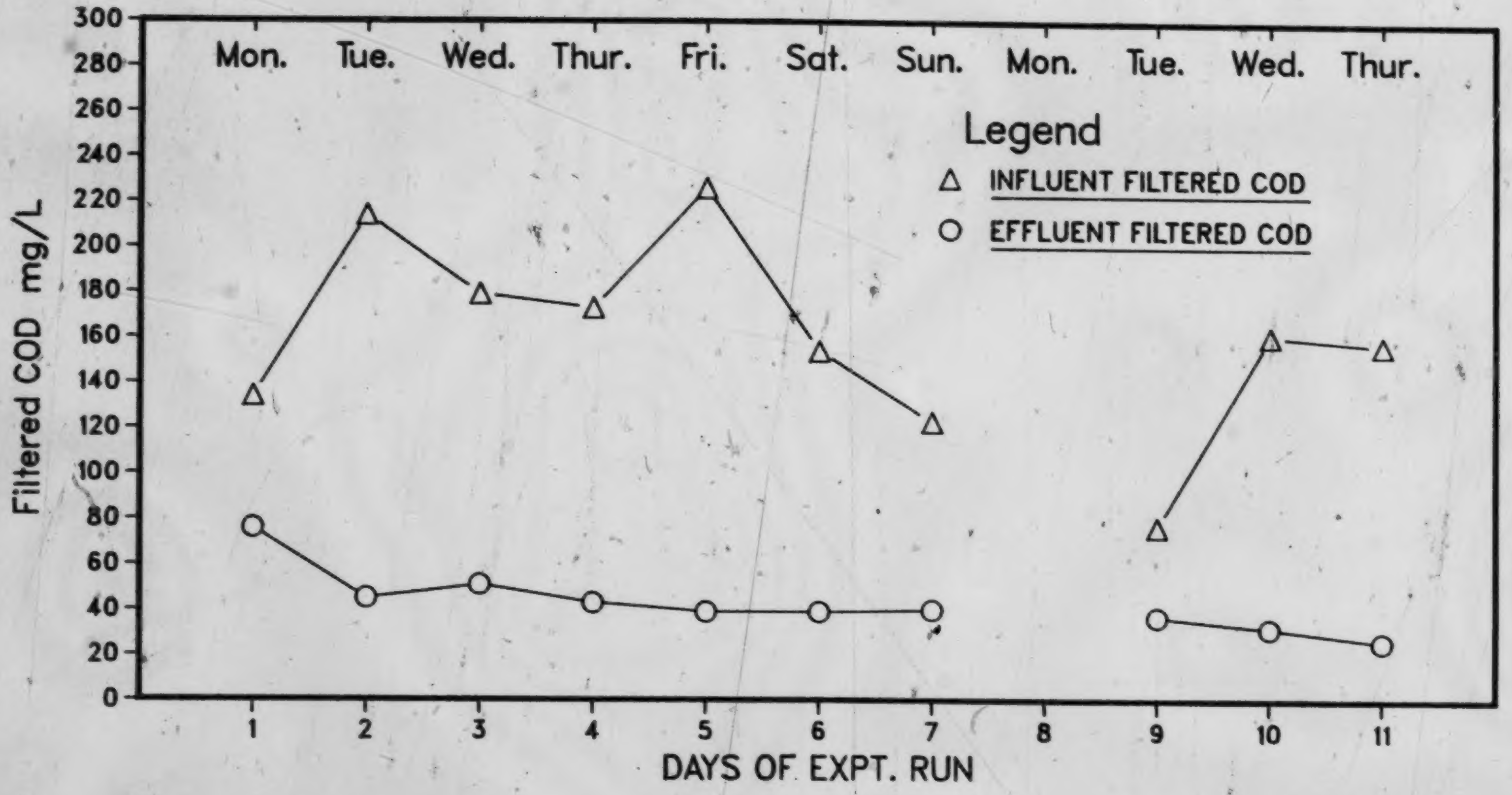


Figure III.26 Influent and Effluent Filtered COD concentrations For Reactor Number Eight Throughout the Sampling Period.

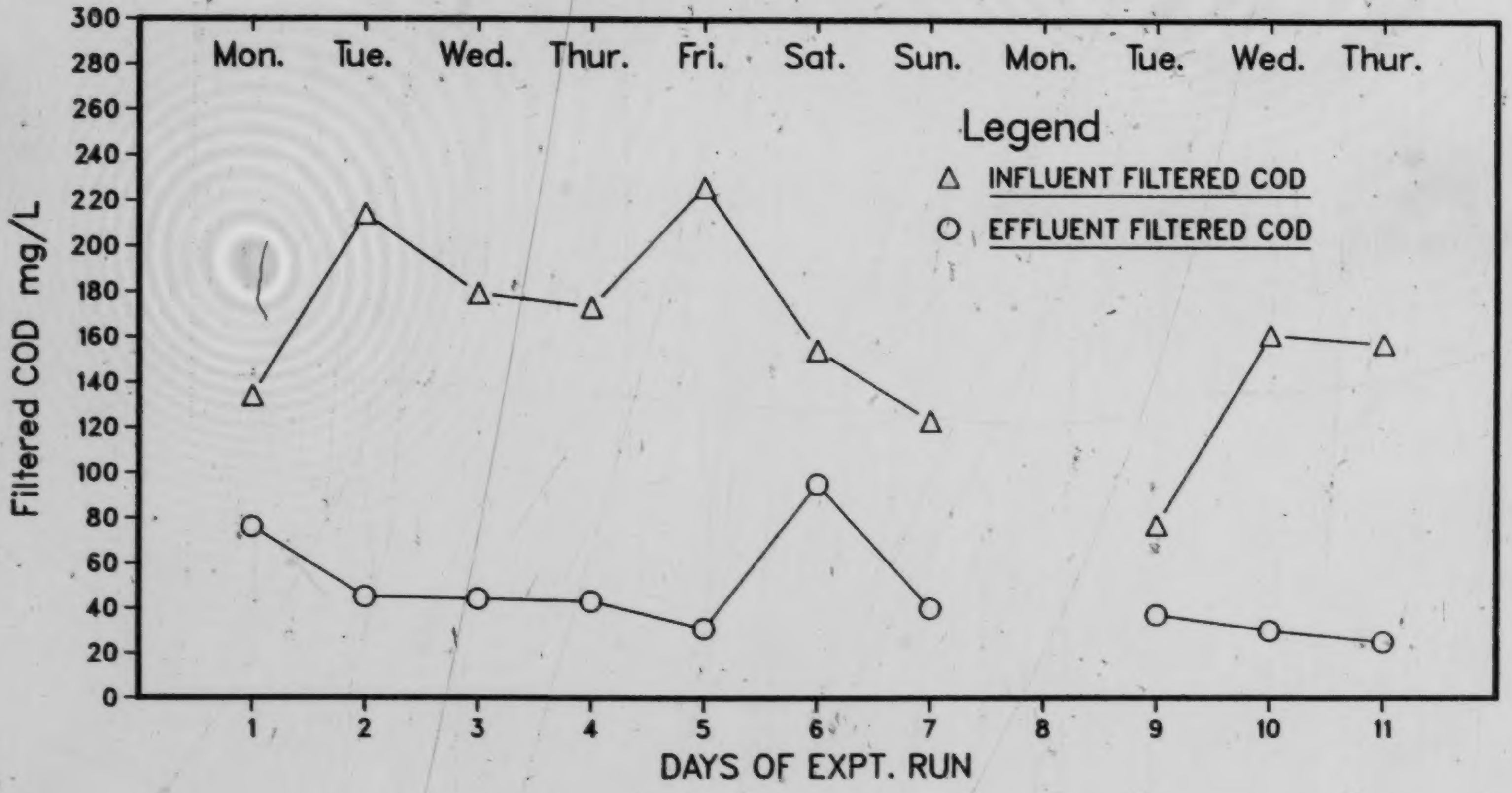


Figure III.27 Influent and Effluent Filtered COD concentrations For Reactor Number Nine Throughout the Sampling Period.

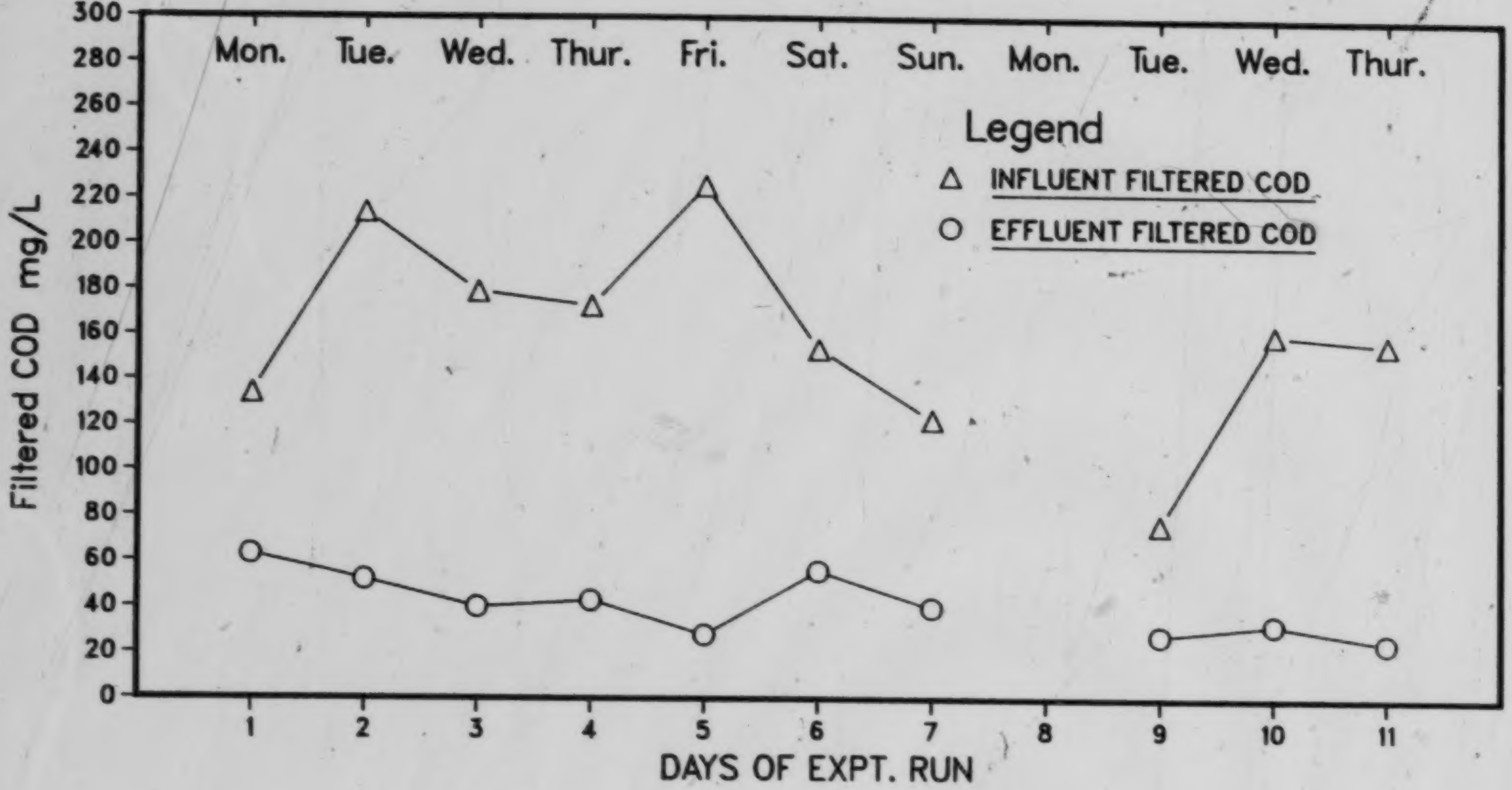


Figure III.28 Influent and Effluent Filtered COD concentrations For Reactor Number Ten Throughout the Sampling Period.

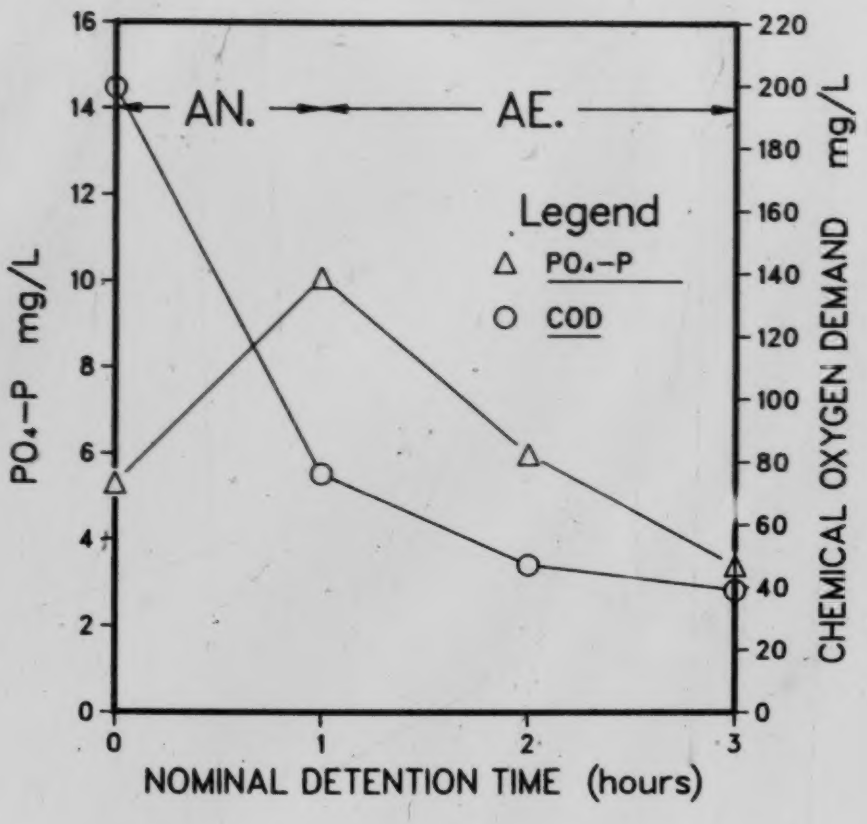


Figure III.29 Profile of Filtered COD and $PO_4$-P Concentration Through Reactor Number One.

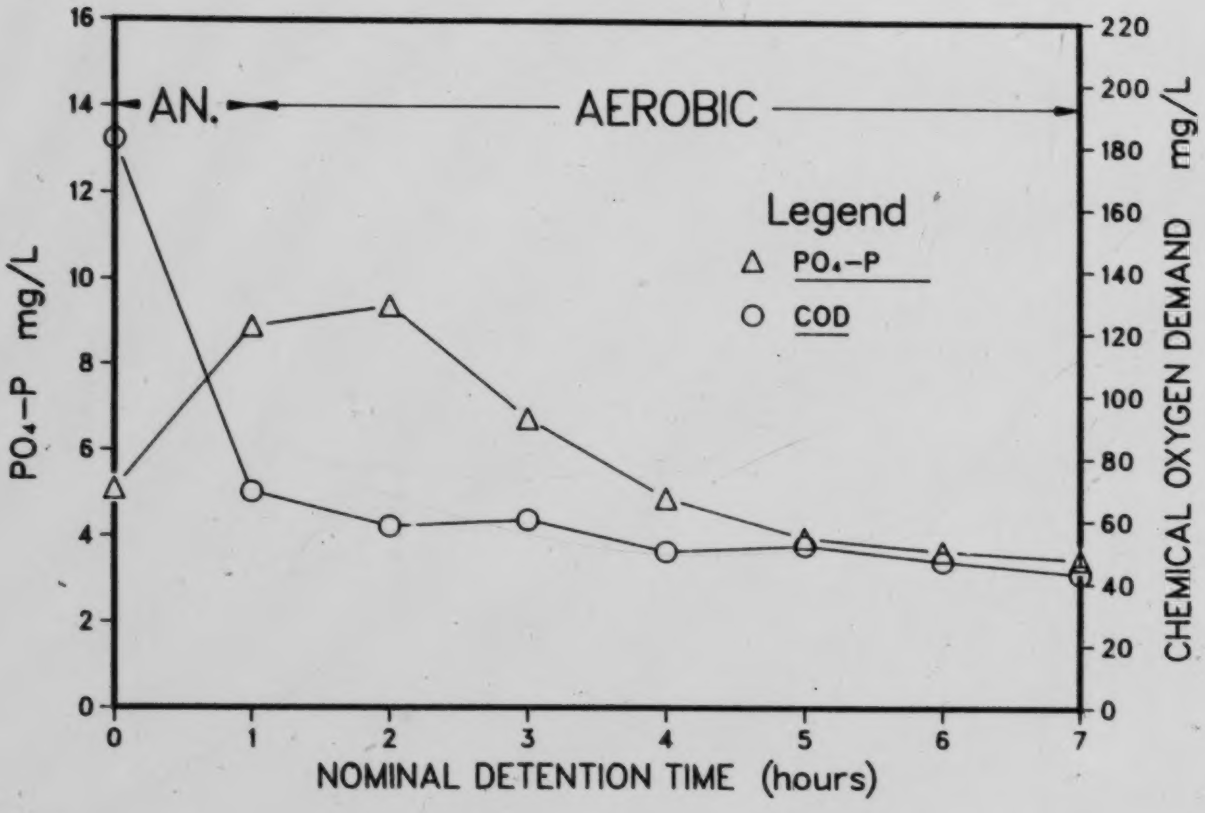
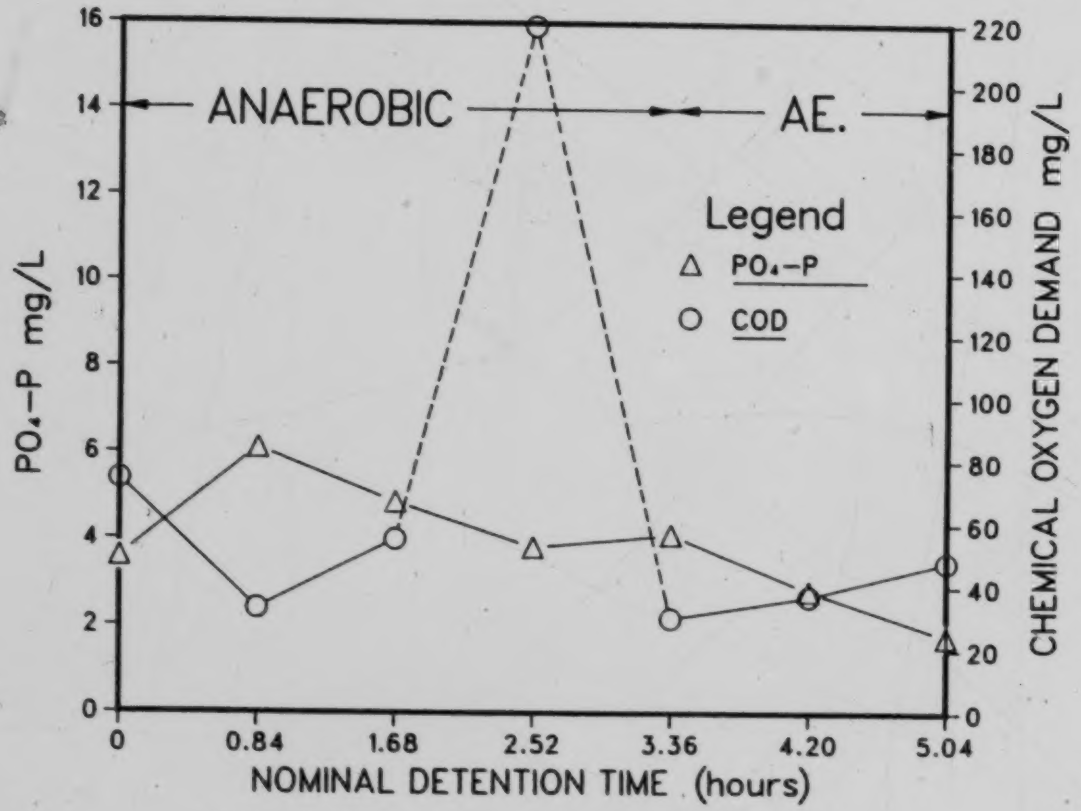


Figure III.30 Profile of Filtered COD and $PO_4$-P Concentration Through Reactor Number Two.



Note: Points joined on both sides by dashed lines are suspected to be in error.

Figure III.31 Profile of Filtered COD and $PO_4$-P Concentration Through Reactor Number Three.

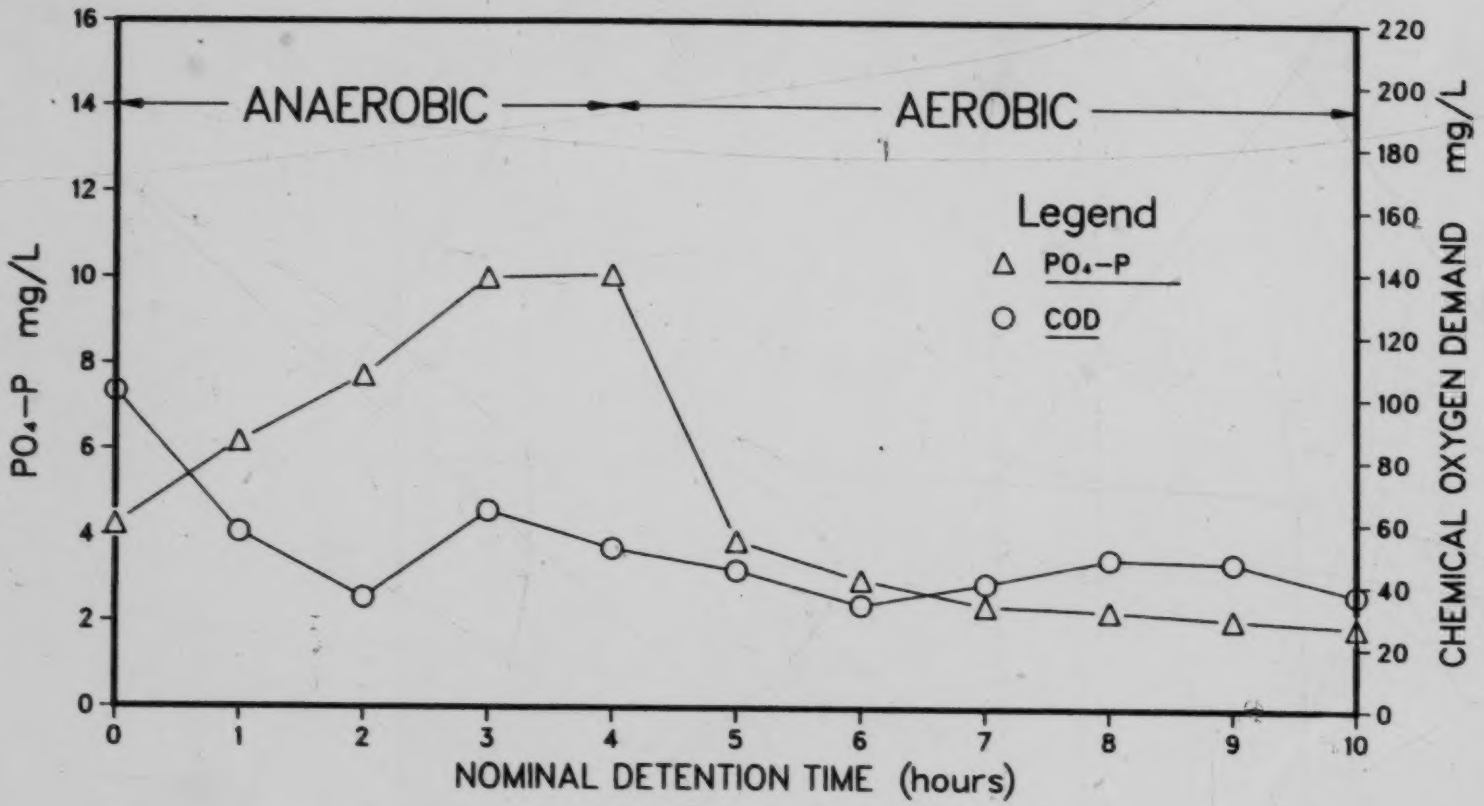


Figure III.32 Profile of Filtered COD and $PO_4$-P Concentration Through Reactor Number Four.

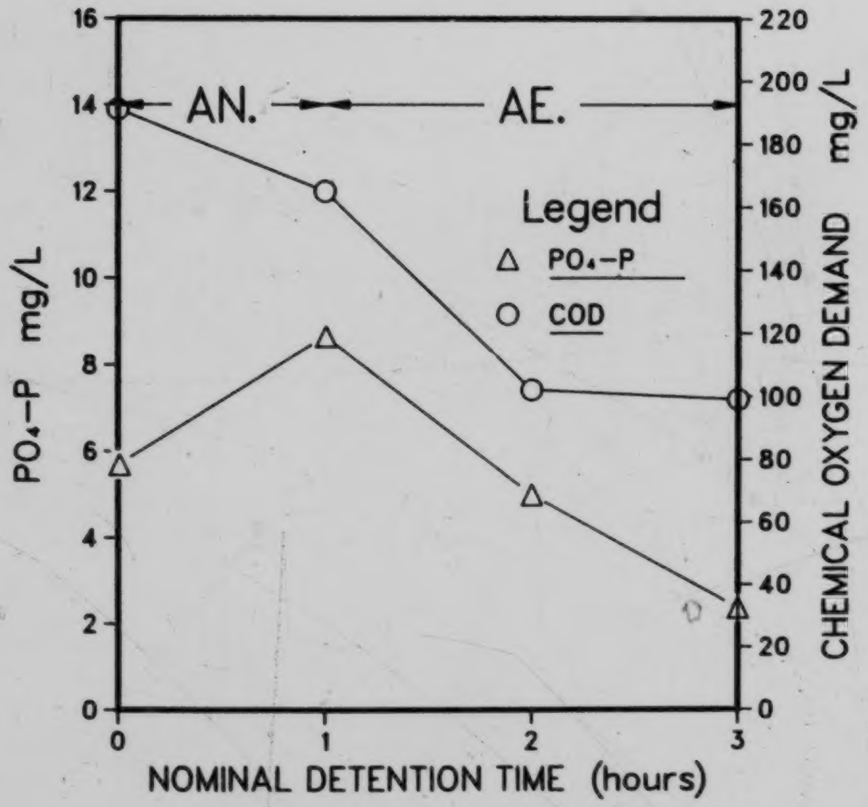
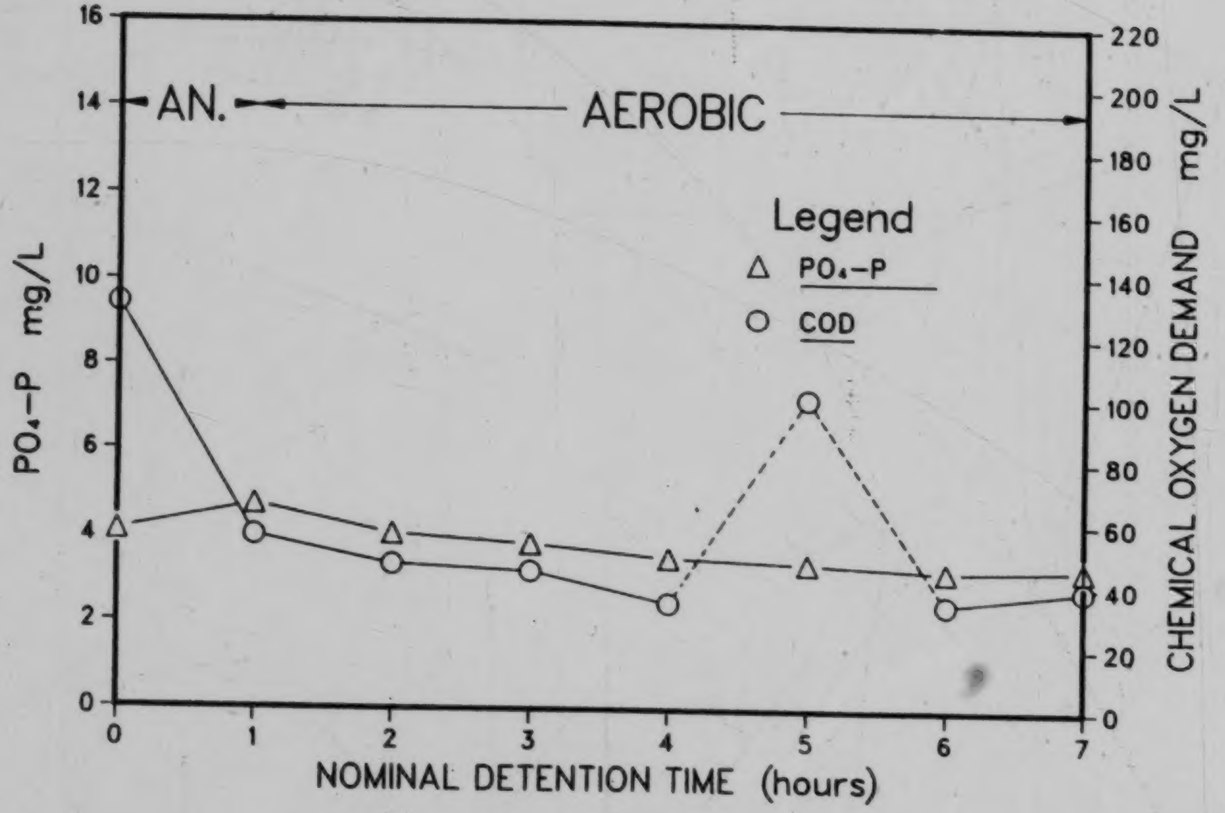
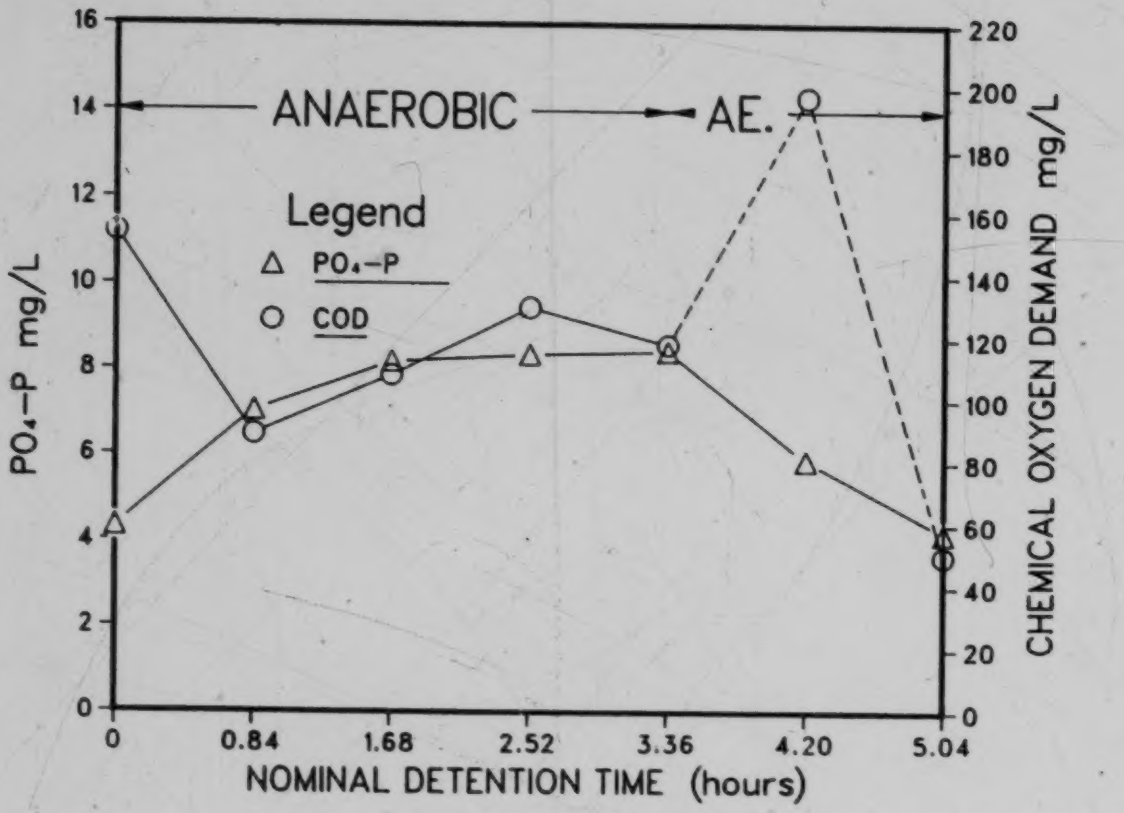


Figure III.33 Profile of Filtered COD and $PO_4$-P Concentration Through Reactor Number Five.



Note: Points joined on both sides by dashed lines are suspected to be in error.

Figure III.34 Profile of Filtered COD and $PO_4$-P Concentration Through Reactor Number Six.



Note: Points joined on both sides by dashed lines are suspected to be in error.

Figure III.35 Profile of Filtered COD and $PO_4$-P Concentration Through Reactor Number Seven.

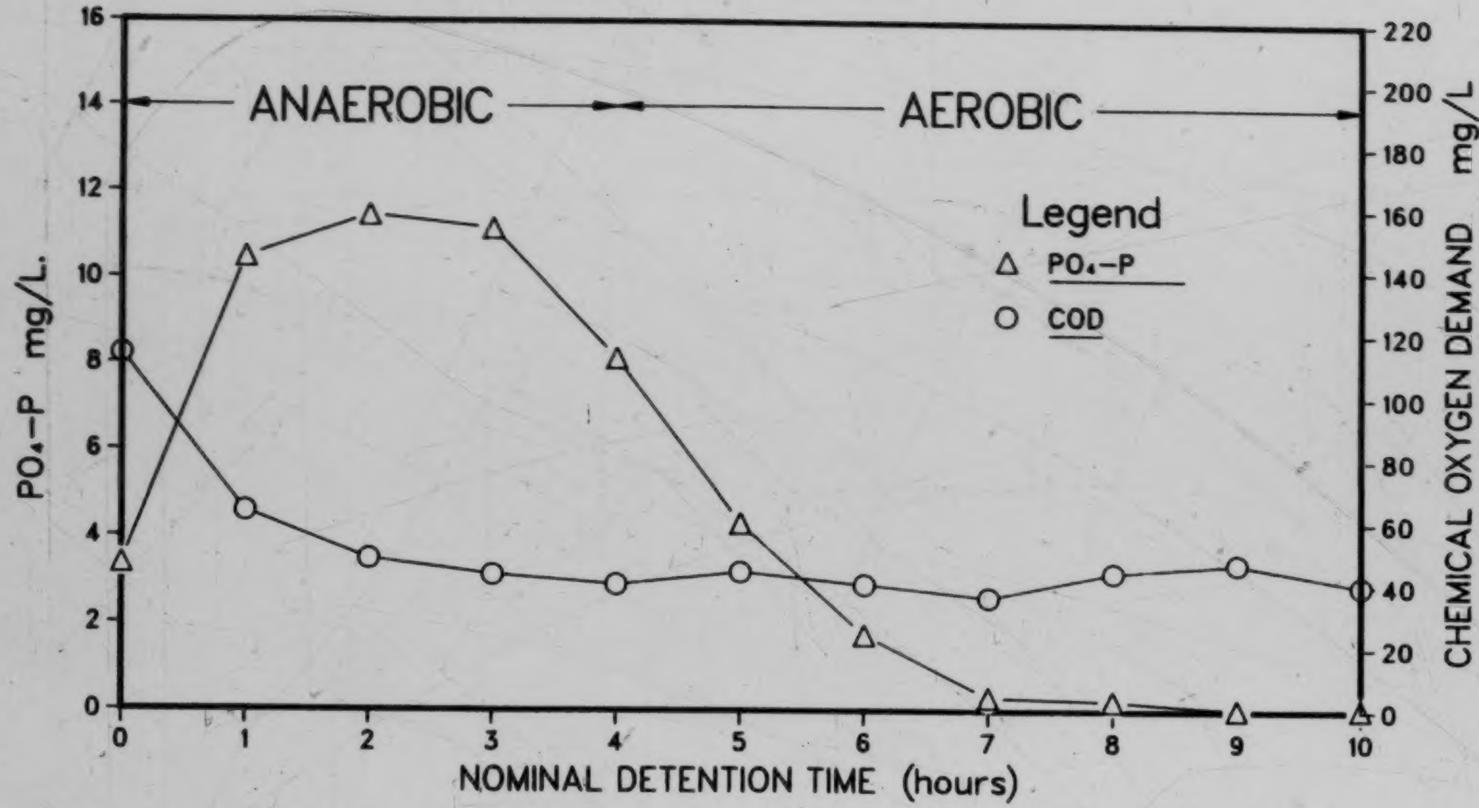


Figure III.36 Profile of Filtered COD and $PO_4$-P Concentration Through Reactor Number Eight.

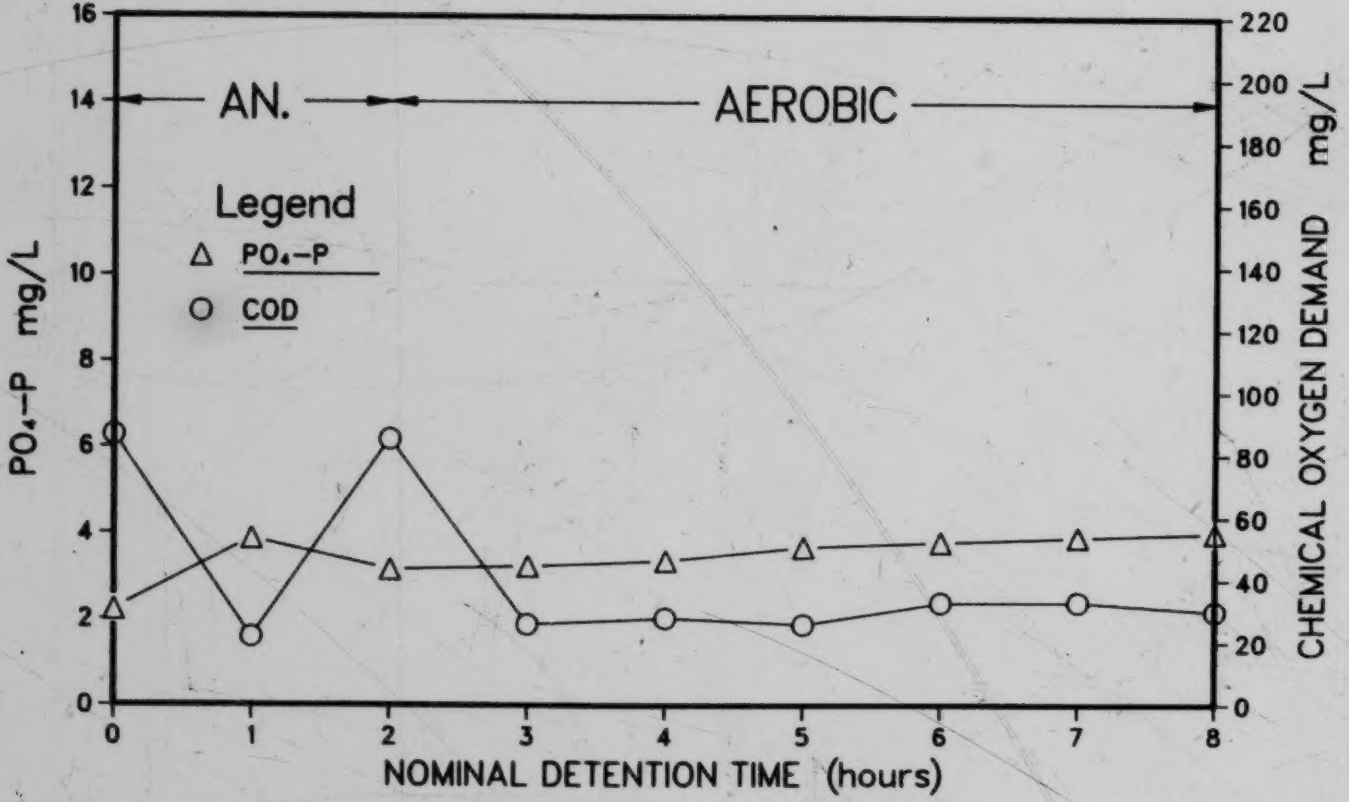


Figure III.37 Profile of Filtered COD and $PO_4$-P Concentration Through Reactor Number Nine.

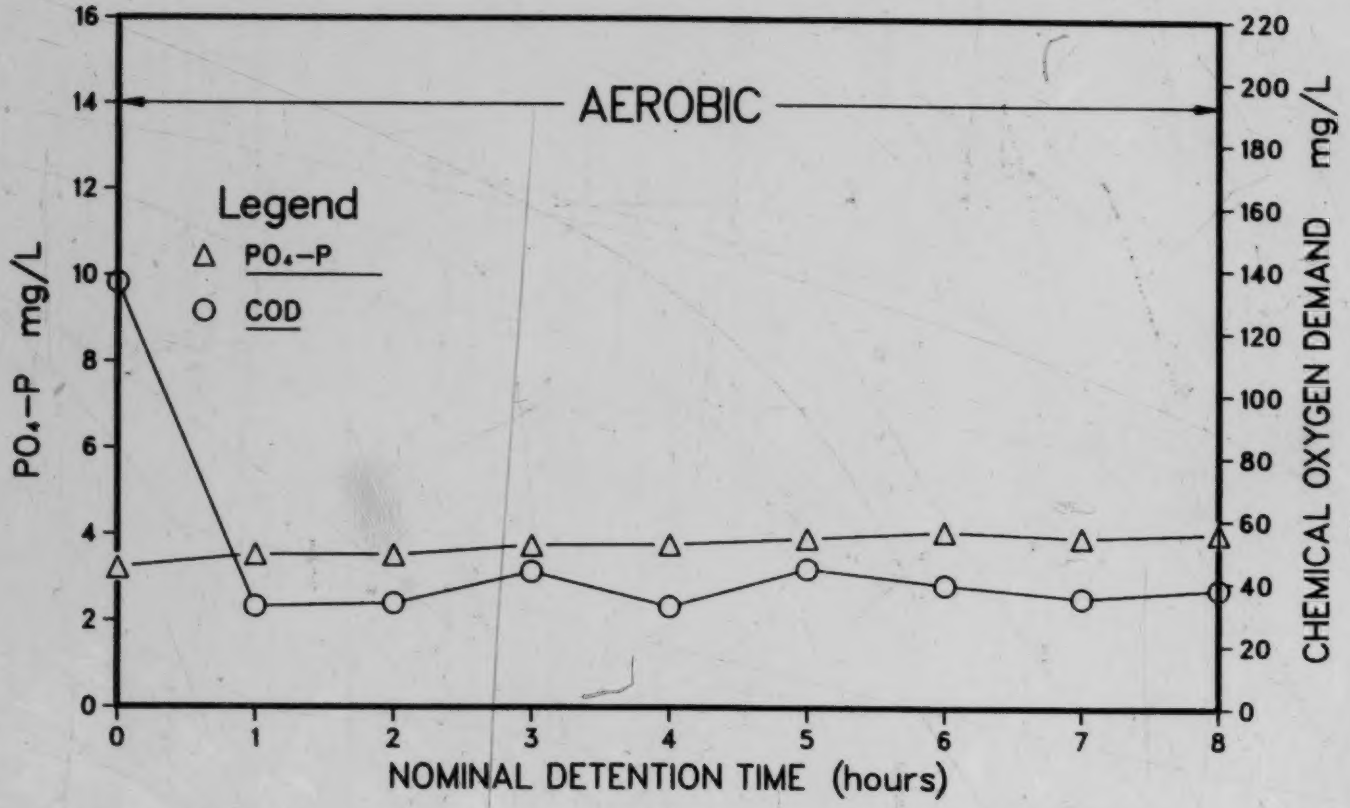


Figure III.38 Profile of Filtered COD and $PO_4$-P Concentration Through Reactor Number Ten.

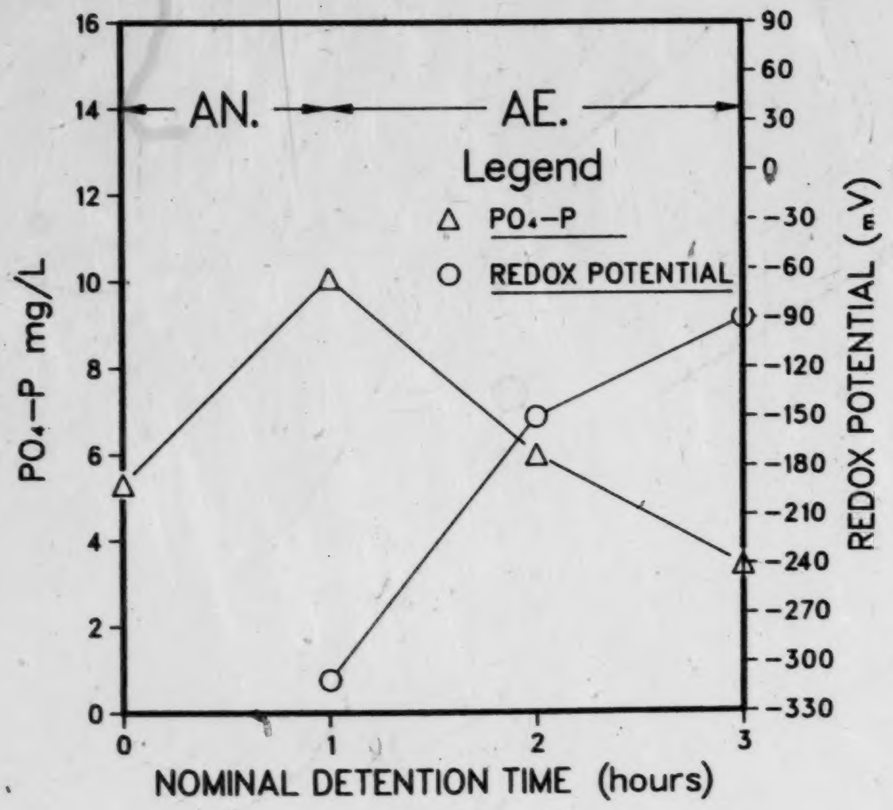


Figure III.39 Profile of Redox Potential and $PO_4$-P Concentration Through Reactor Number One.

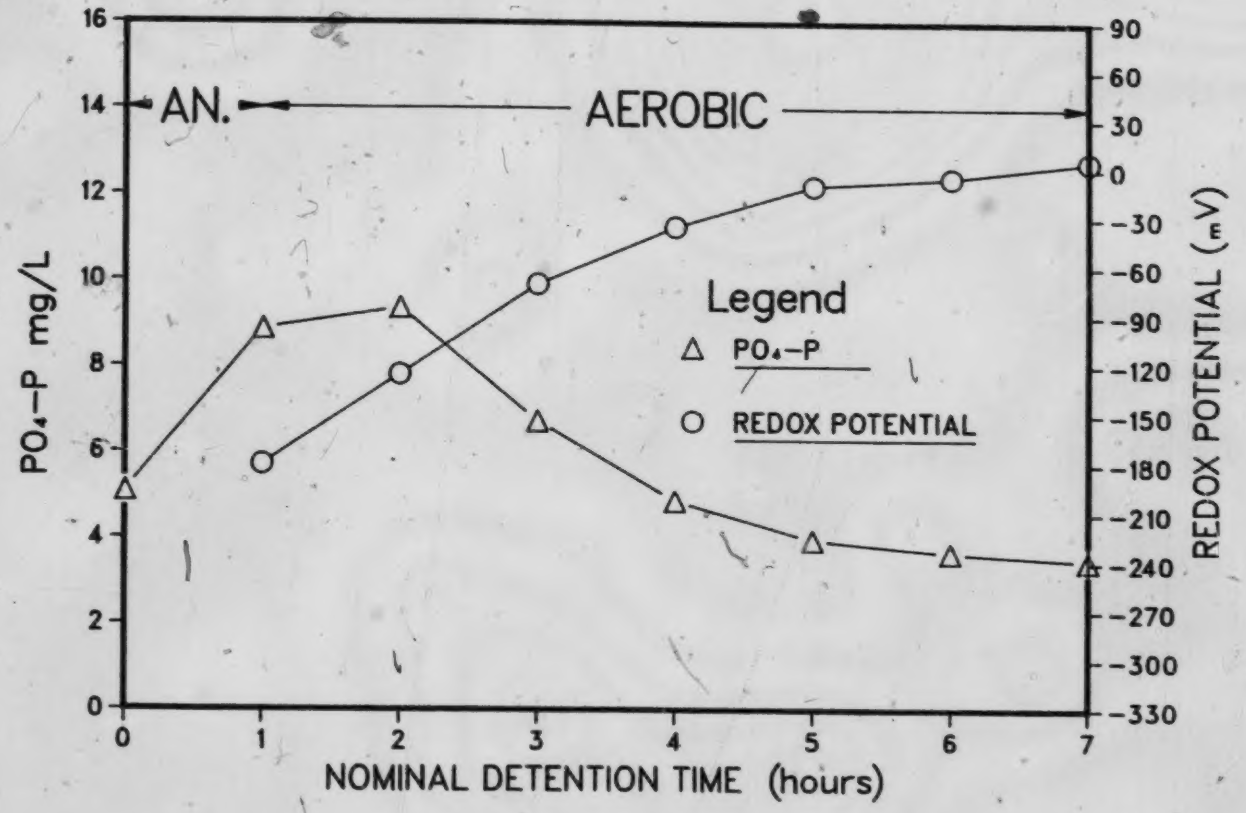


Figure III.40 Profile of Redox Potential and $PO_4$-P Concentration Through Reactor Number Two.

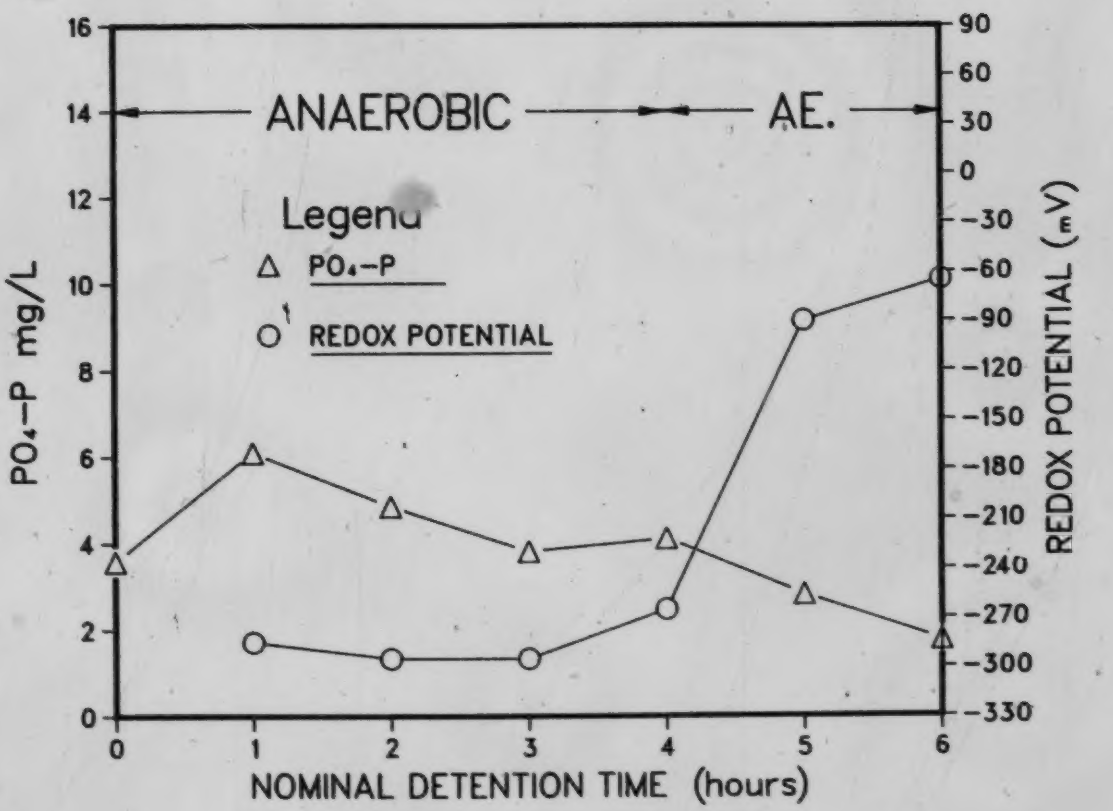


Figure III.41 Profile of Redox Potential and $PO_4$-P Concentration Through Reactor Number Three.

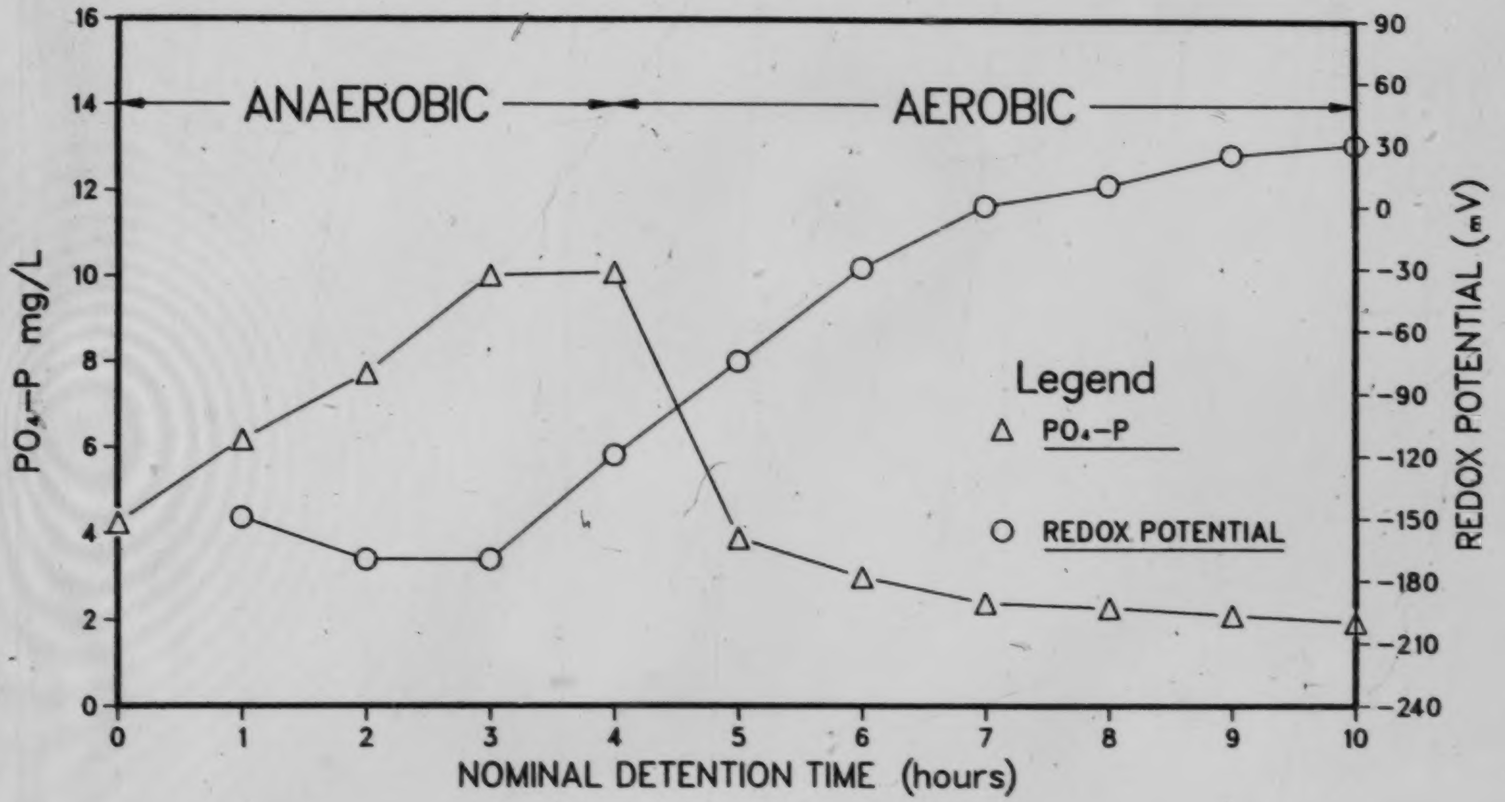


Figure III.42 Profile of Redox Potential and $PO_4$-P Concentration Through Reactor Number Four.

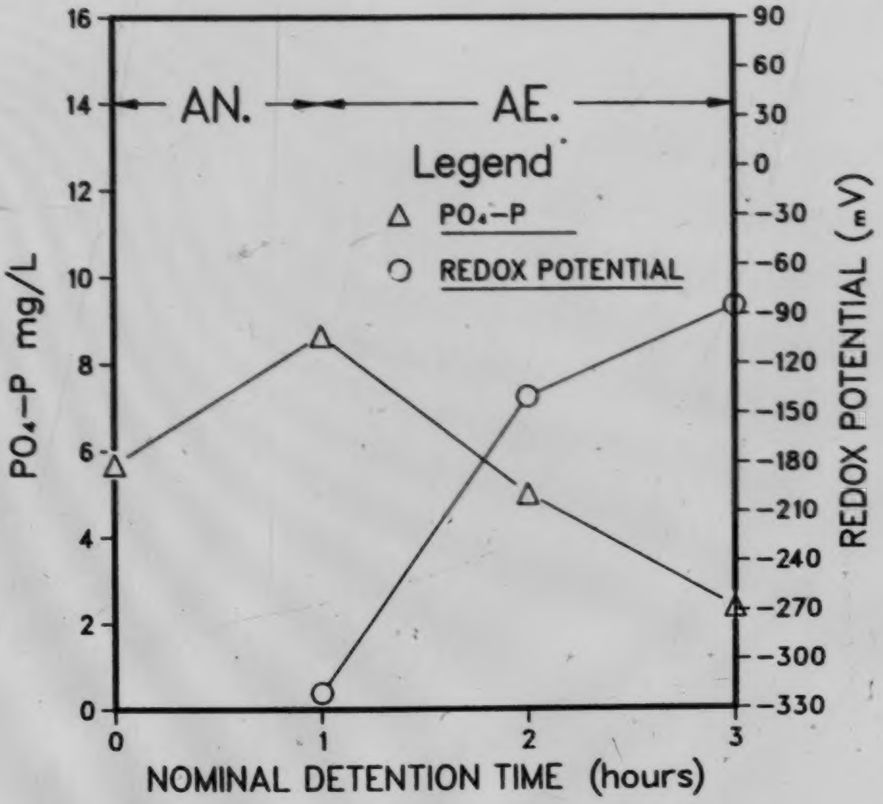


Figure III.43 Profile of Redox Potential and $PO_4$-P Concentration Through Reactor Number Five.

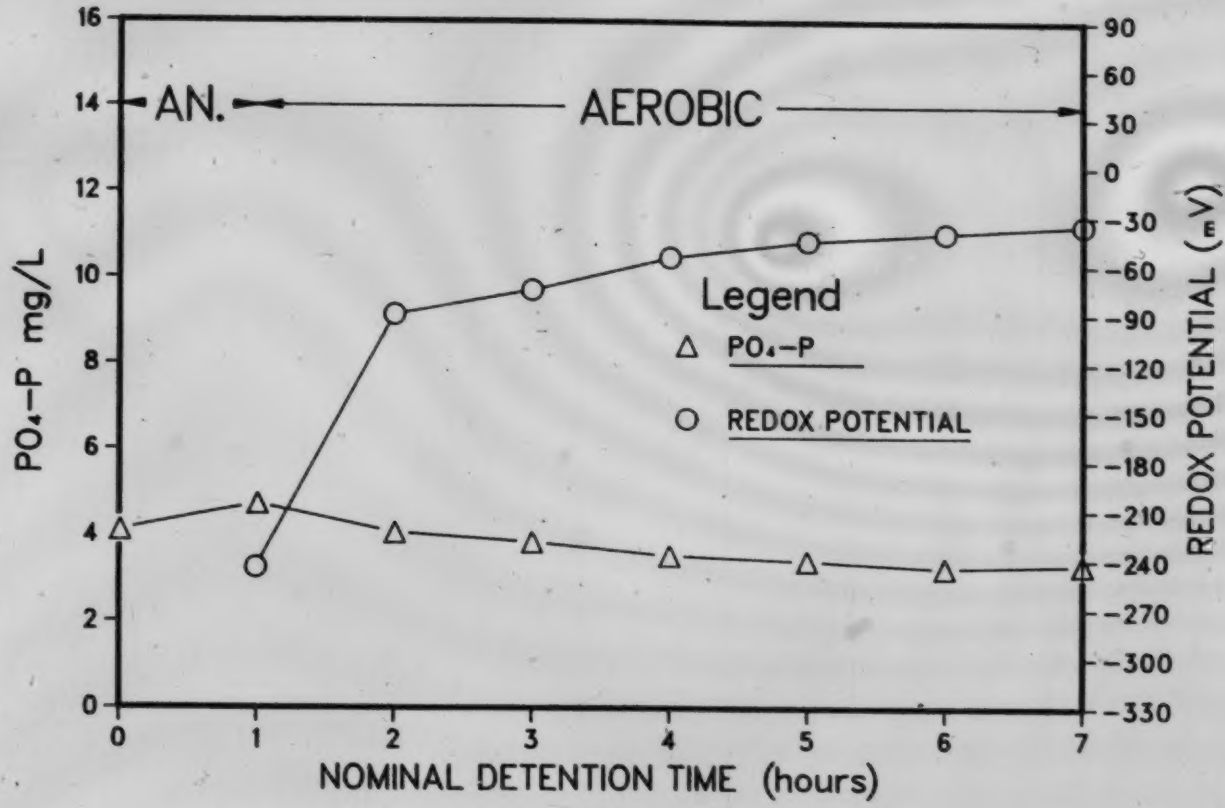


Figure III.44 Profile of Redox Potential and $PO_4$-P Concentration Through Reactor Number Six.

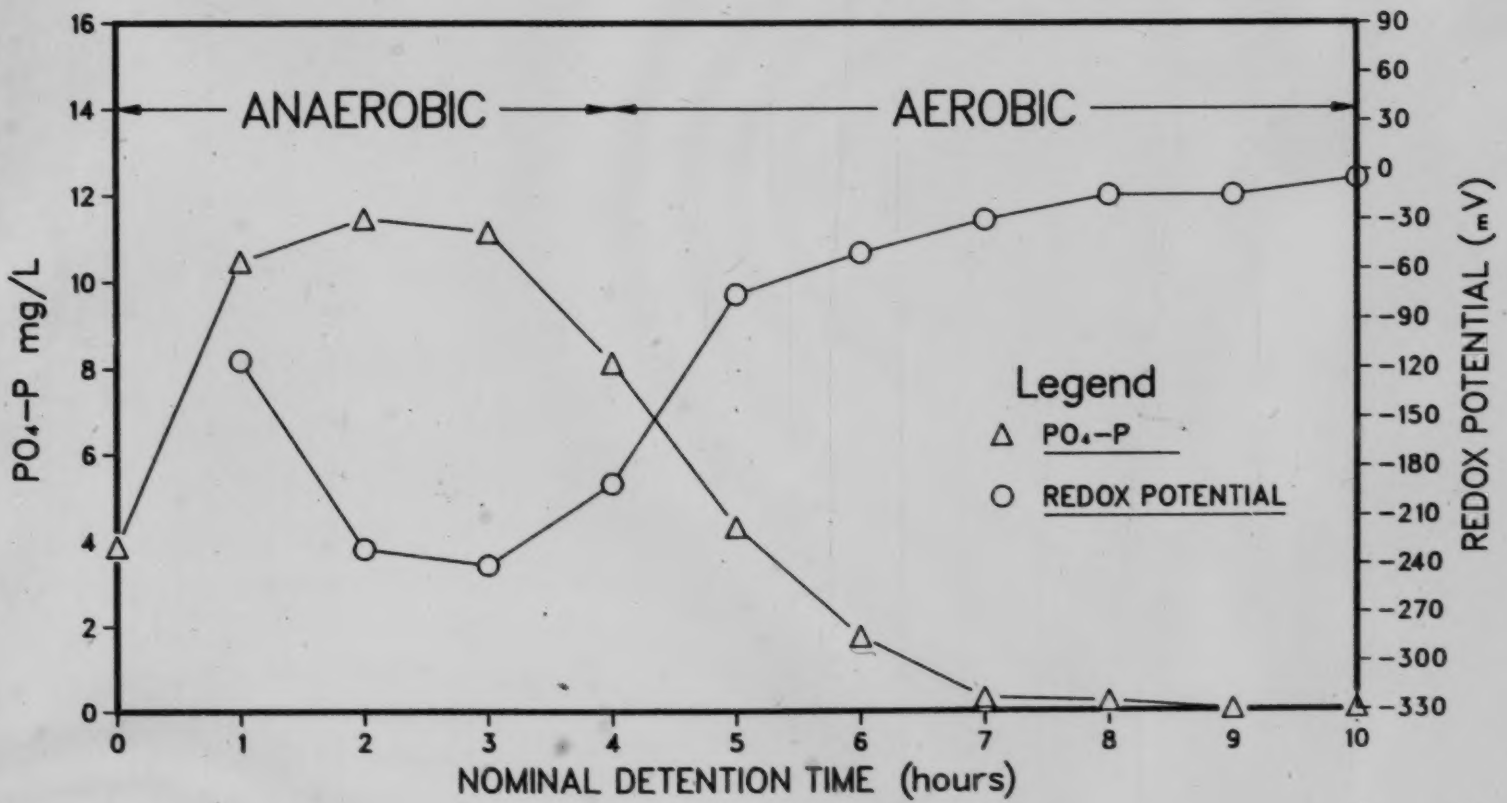


Figure III.45 Profile of Redox Potential and $PO_4$-P Concentration Through Reactor Number Eight.

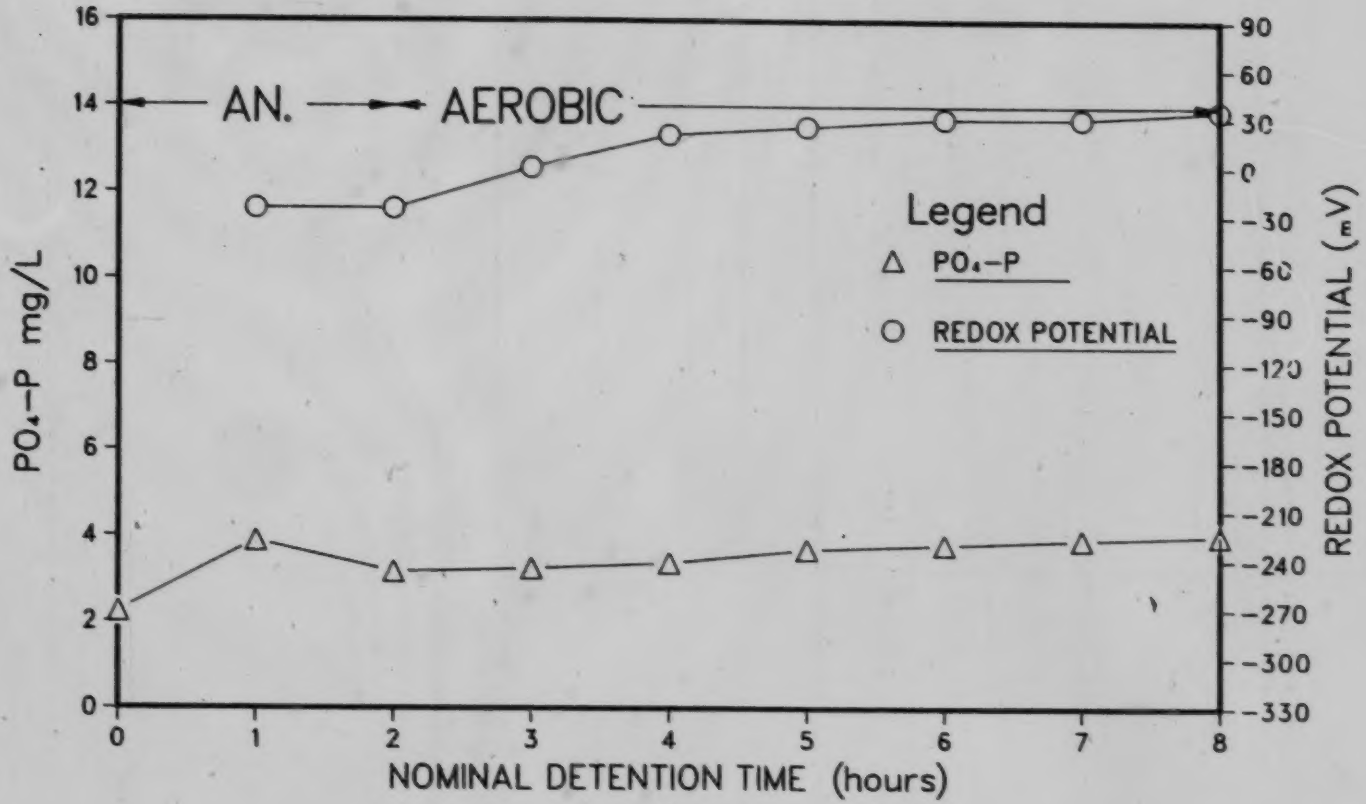


Figure III.46 Profile of Redox Potential and $PO_4$-P Concentration Through Reactor Number Nine.

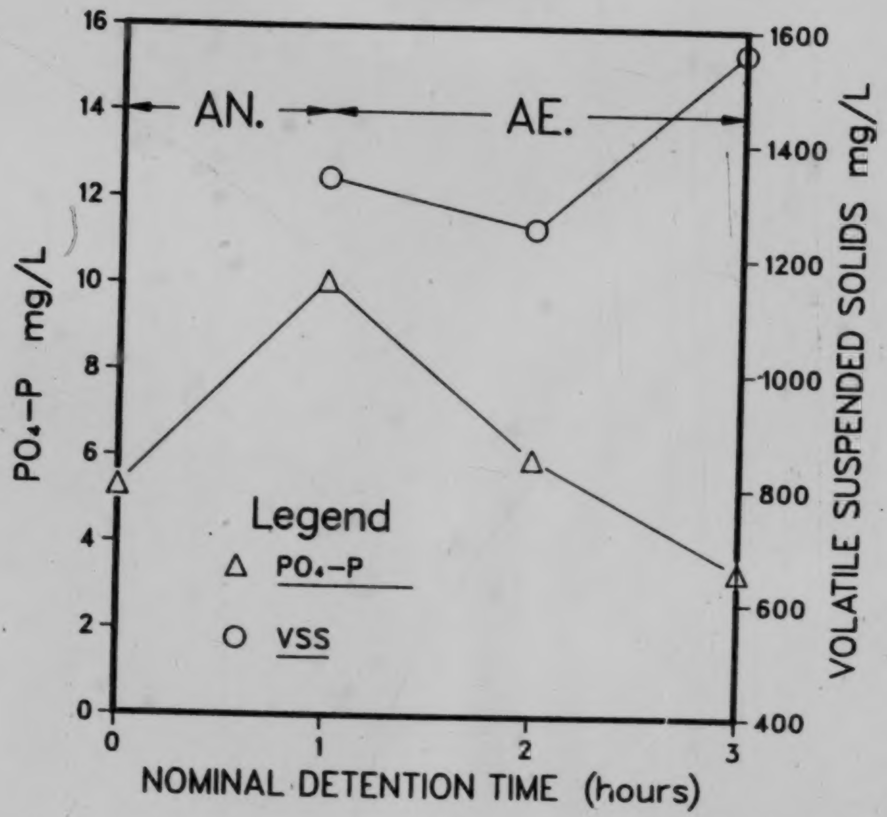


Figure III.47 Profile of VSS and $PO_4$-P Concentration Through Reactor Number One.

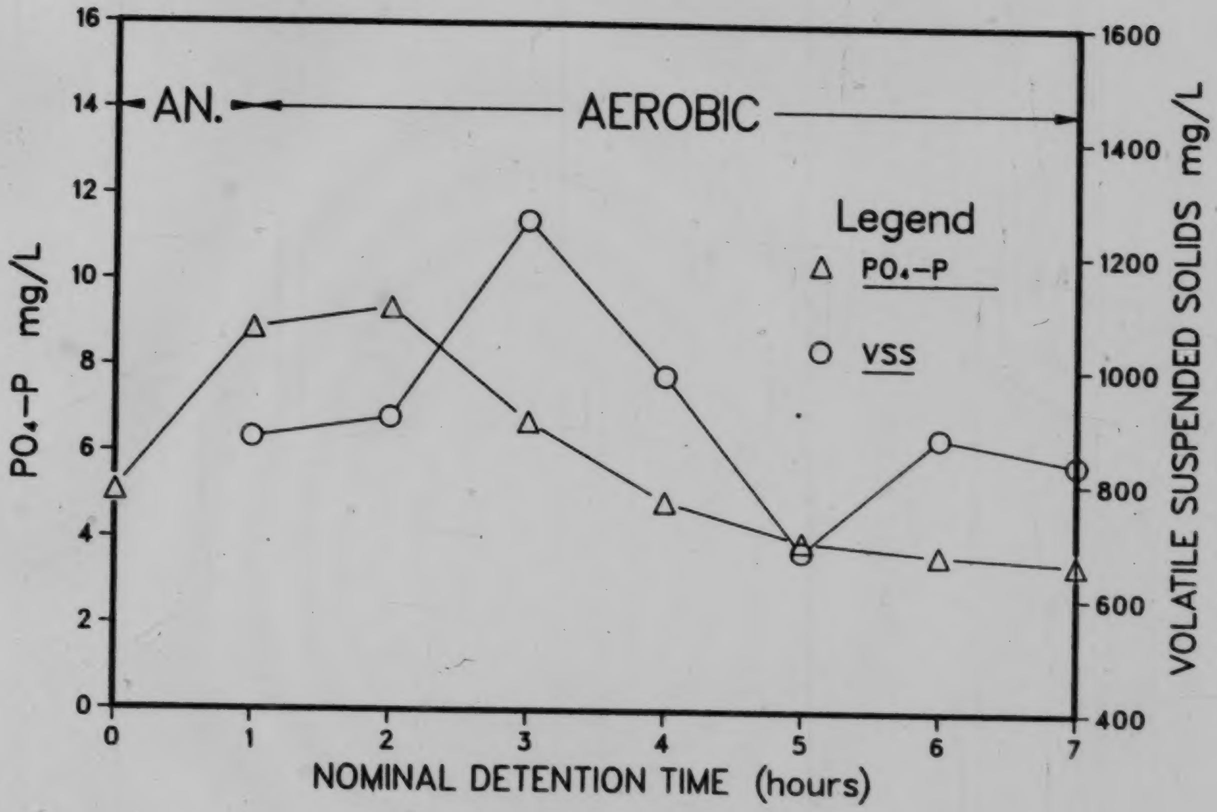


Figure III.48 Profile of VSS and $PO_4$-P Concentration Through Reactor Number Two.

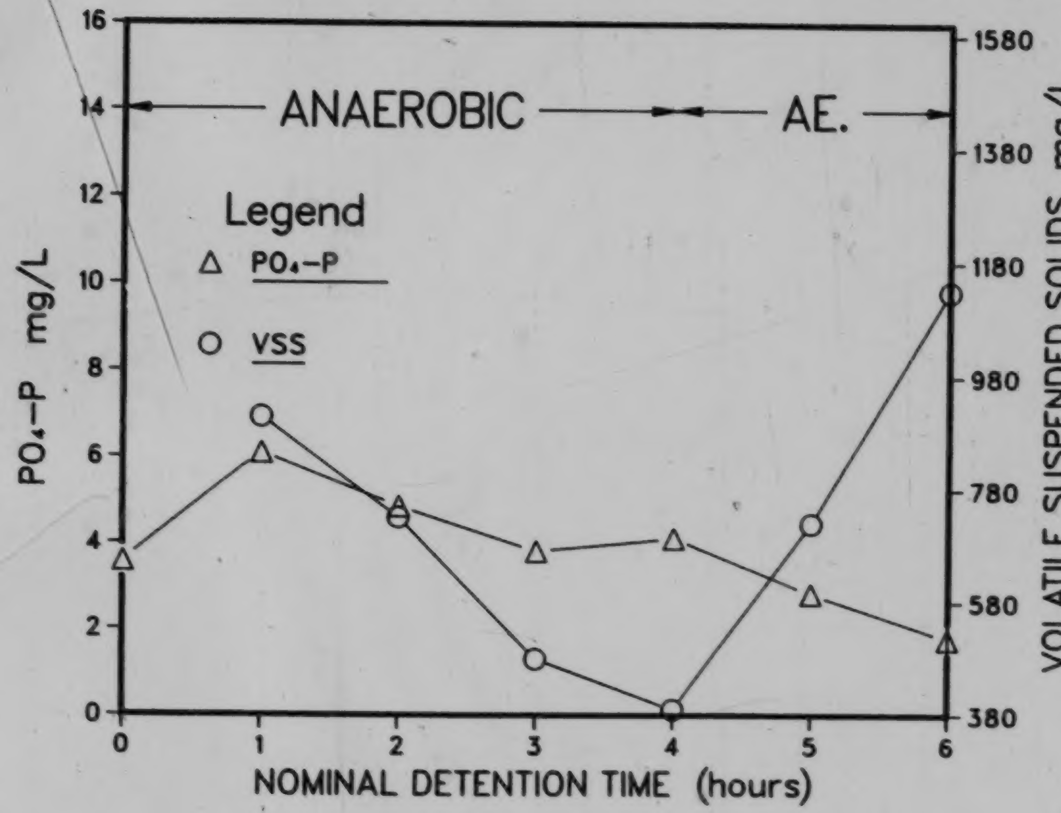


Figure III.49 Profile of VSS and $PO_4$-P Concentration Through Reactor Number Three.

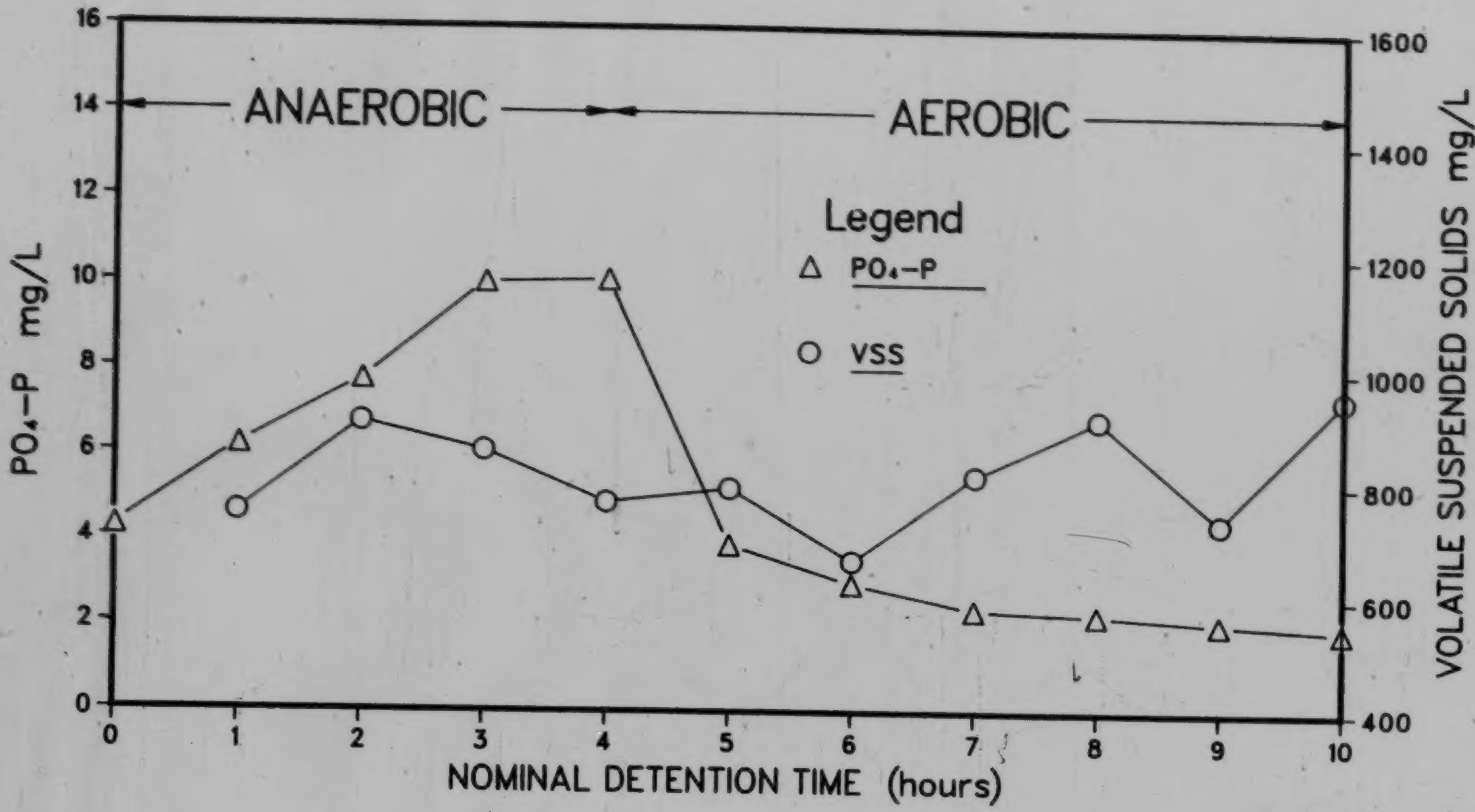


Figure III.50 Profile of VSS and $PO_4$-P Concentration Through Reactor Number Four.

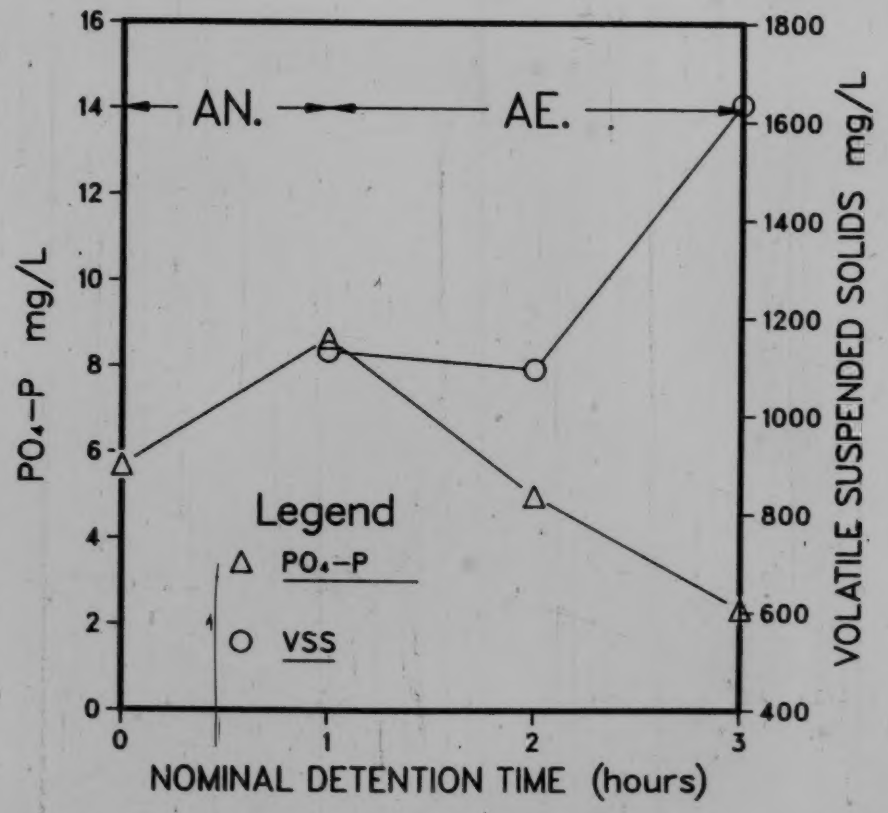


Figure III.51 Profile of VSS and $PO_4$-P Concentration Through Reactor Number Five.

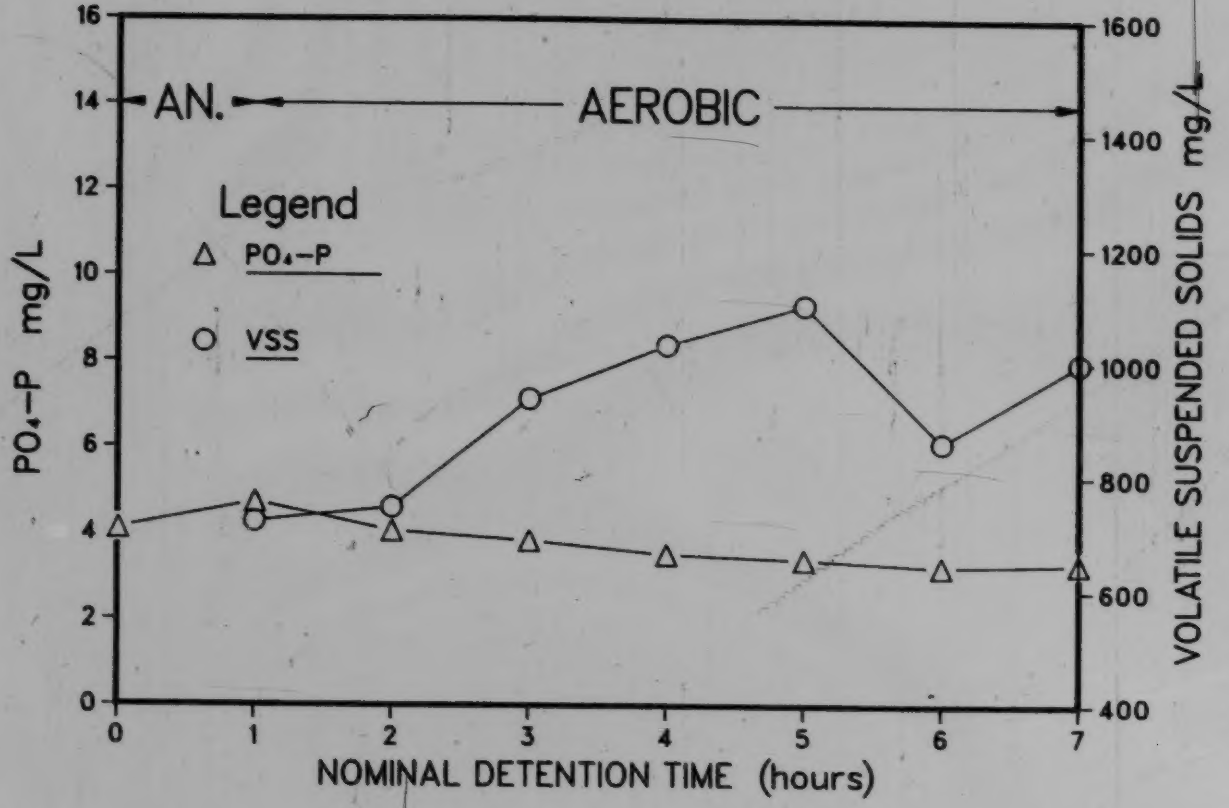


Figure III.52 Profile of VSS and $PO_4$-P Concentration Through Reactor Number Six.

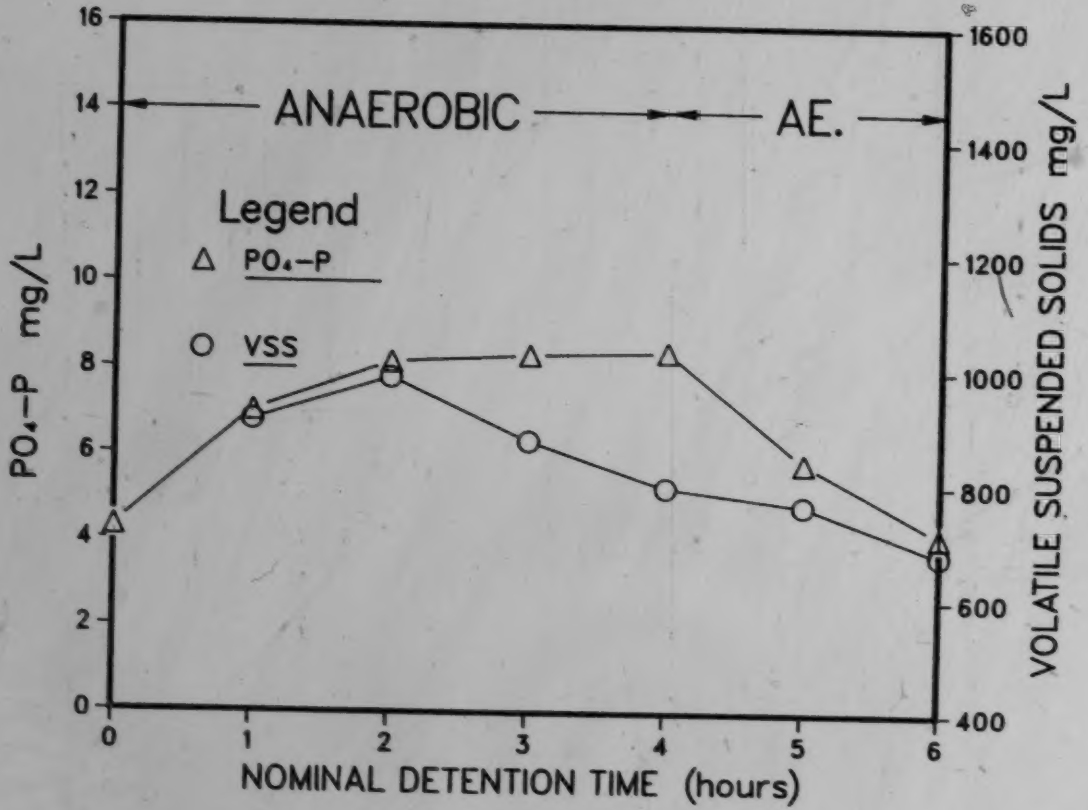


Figure III.53 Profile of VSS and $PO_4$-P Concentration Through Reactor Number Seven.

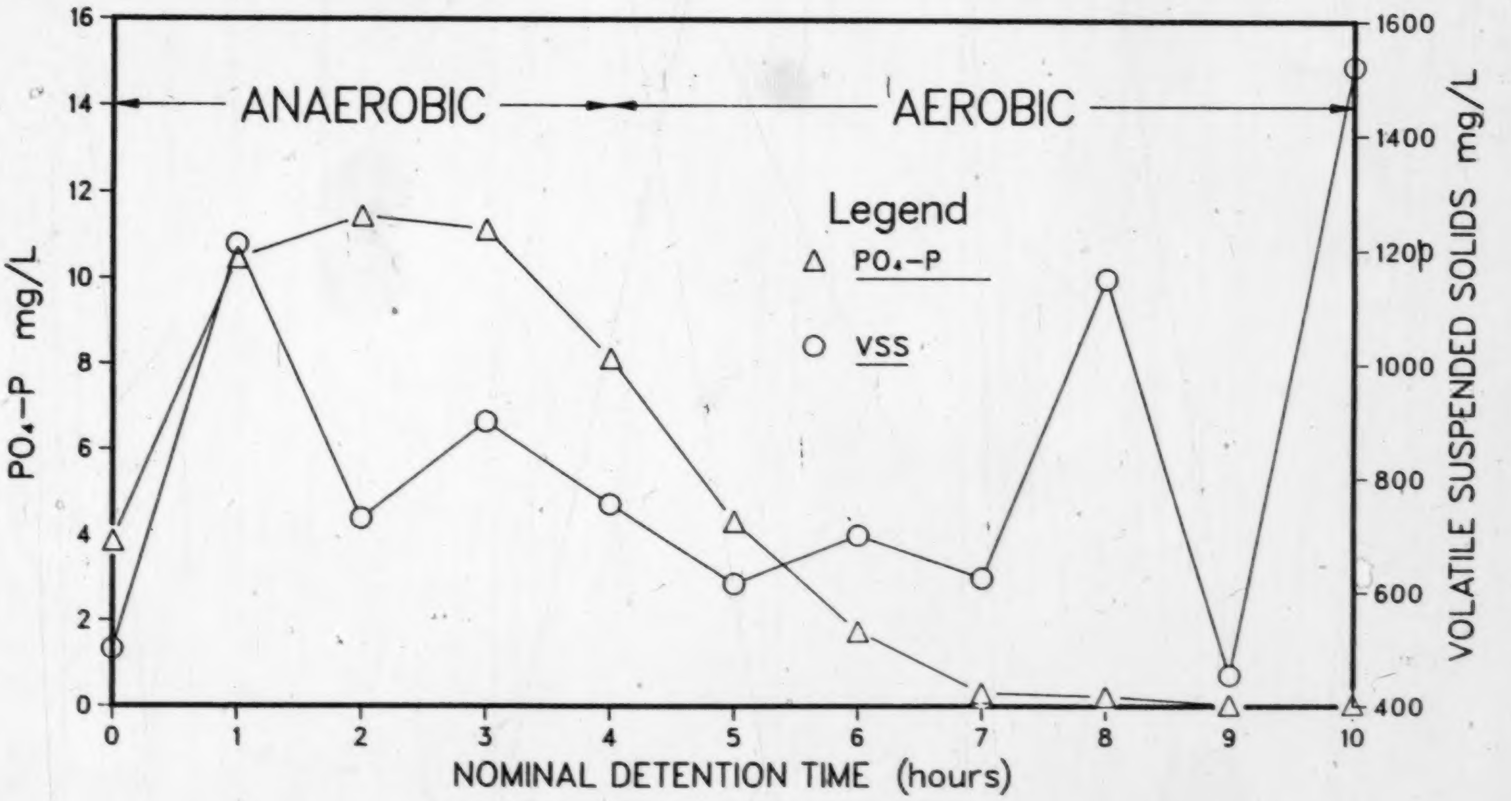


Figure III.54 Profile of VSS and $PO_4$-P Concentration Through Reactor Number Eight.

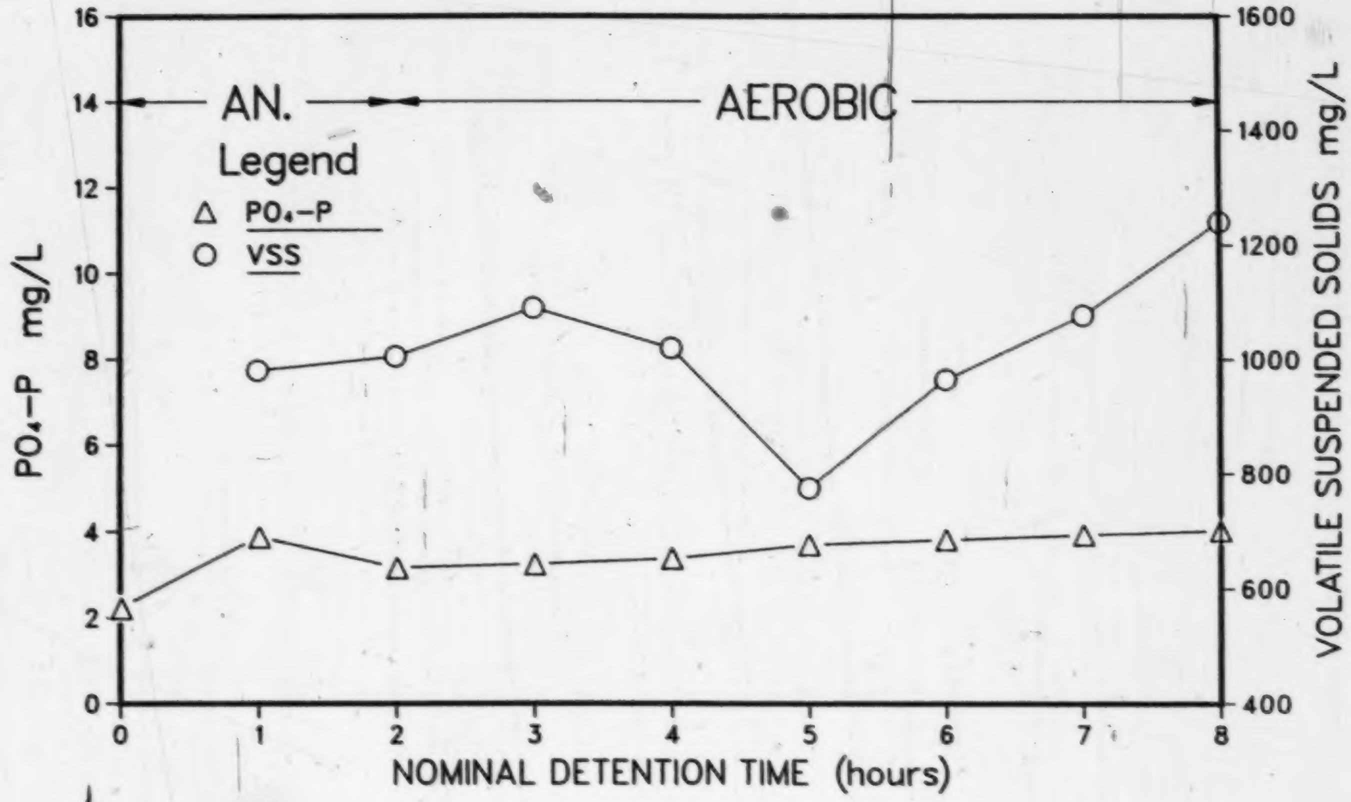


Figure III.55 Profile of VSS and $PO_4$-P Concentration Through Reactor Number Nine.

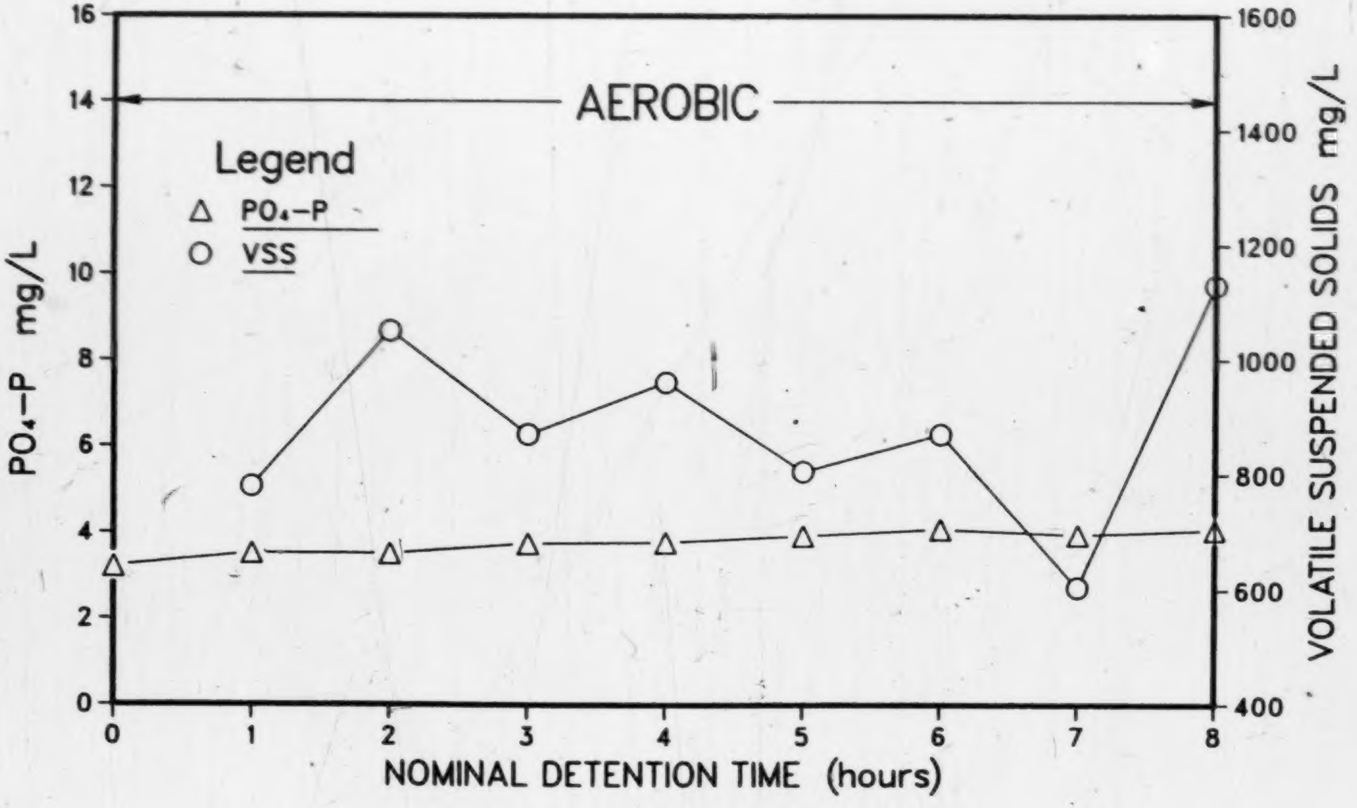


Figure III.56 Profile of VSS and $PO_4$-P Concentration Through Reactor Number Ten.

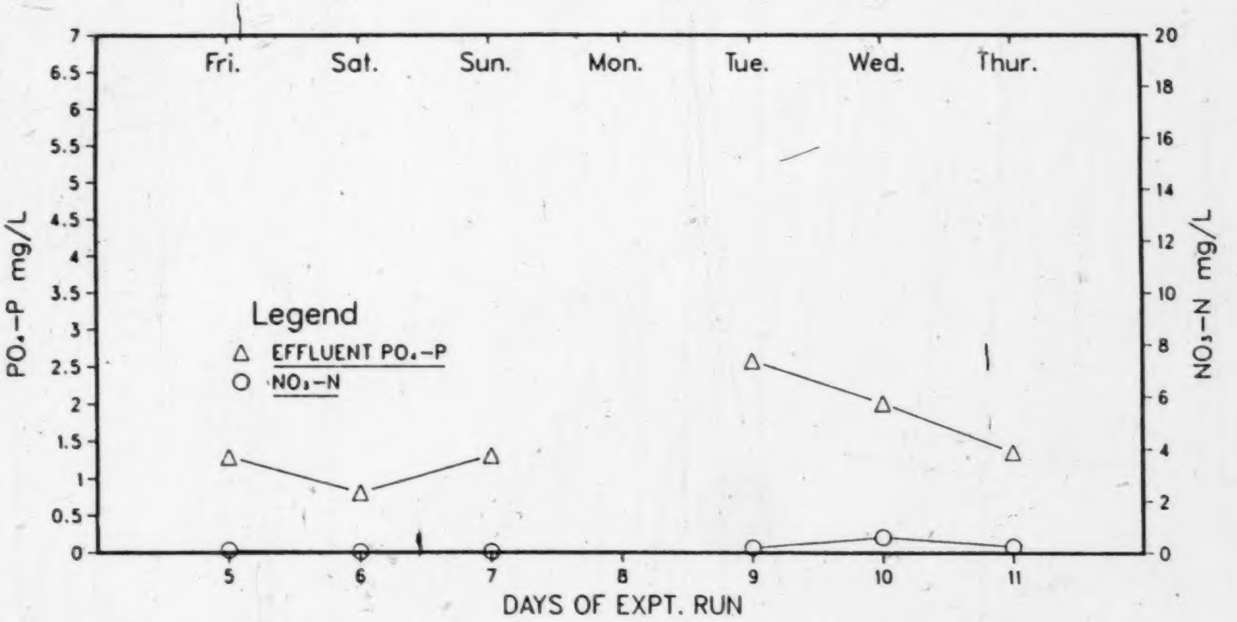


Figure III.57 Effluent $PO_4$-P and Effluent $NO_3$-N For Reactor Number One Throughout the Sampling Period.

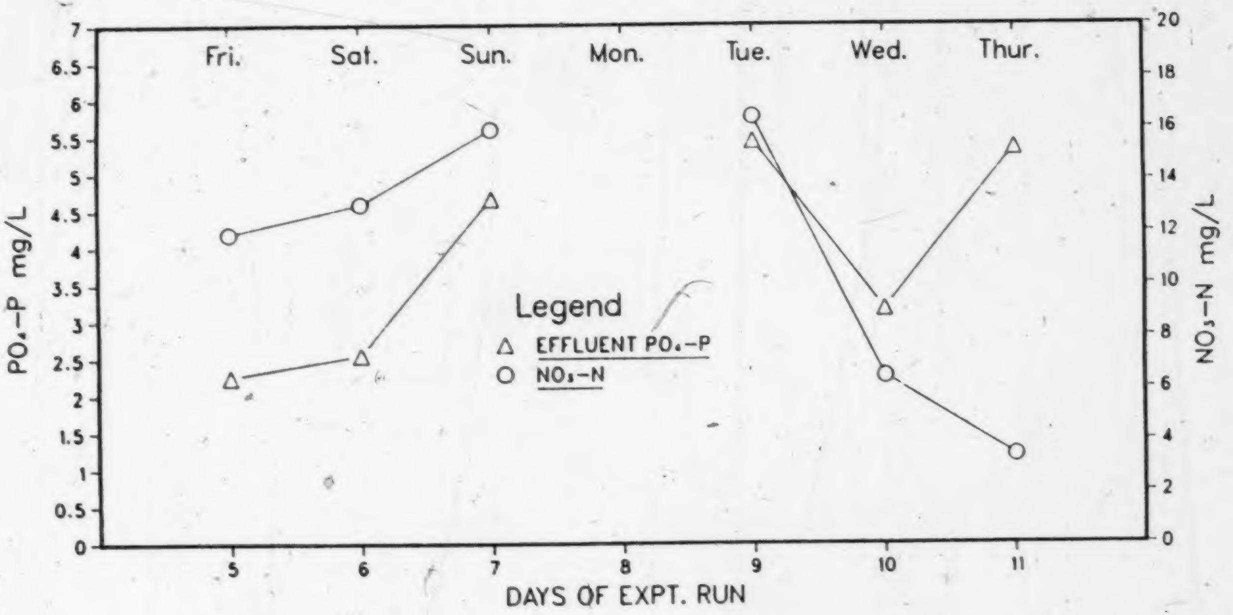


Figure III.58 Effluent $PO_4$-P and Effluent $NO_3$-N For Reactor Number Two Throughout the Sampling Period.

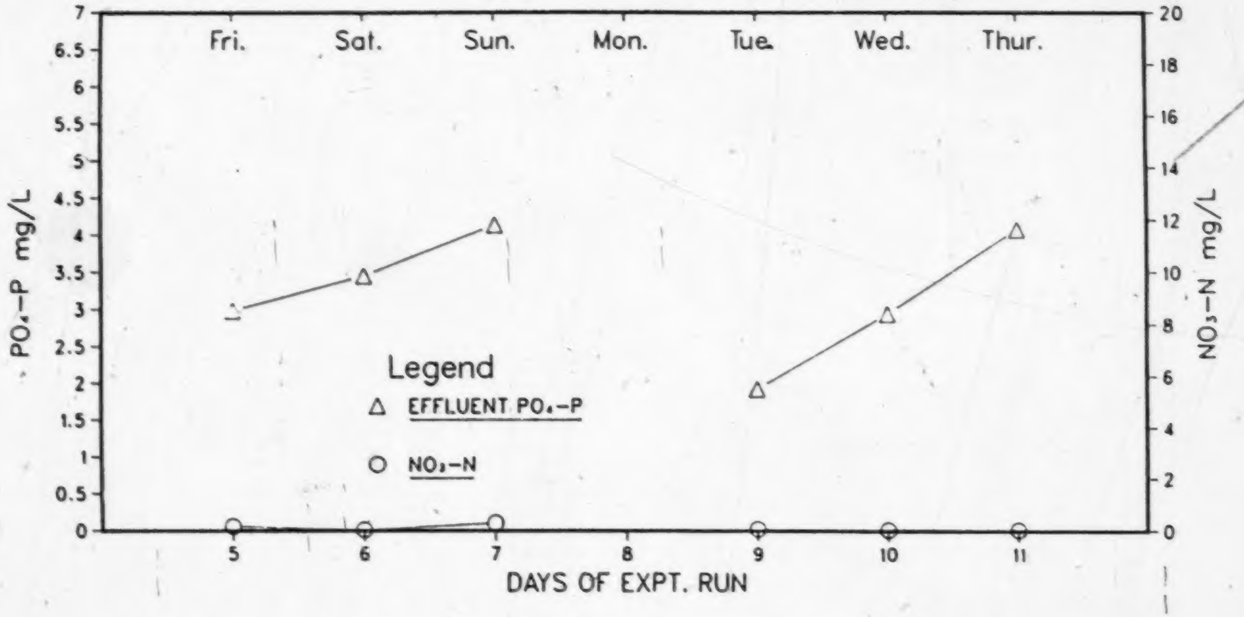


Figure III.59 Effluent $PO_4$-P and Effluent $NO_3$-N For Reactor Number Three Throughout the Sampling Period.

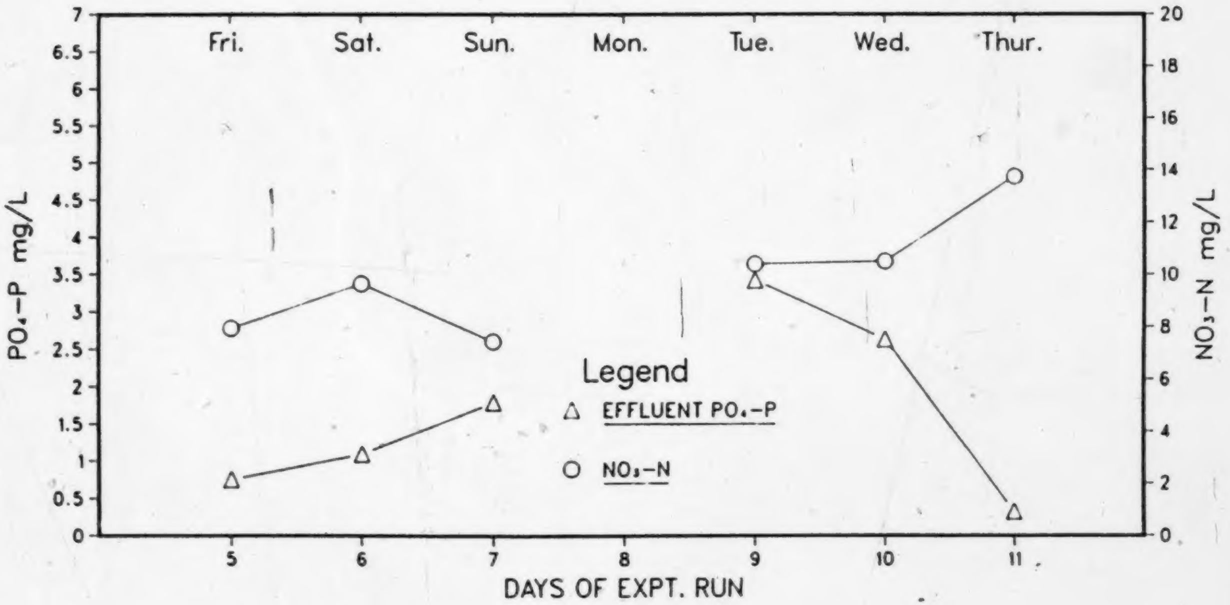


Figure III.60 Effluent $PO_4$-P and Effluent $NO_3$-N For Reactor Number Four Throughout the Sampling Period.

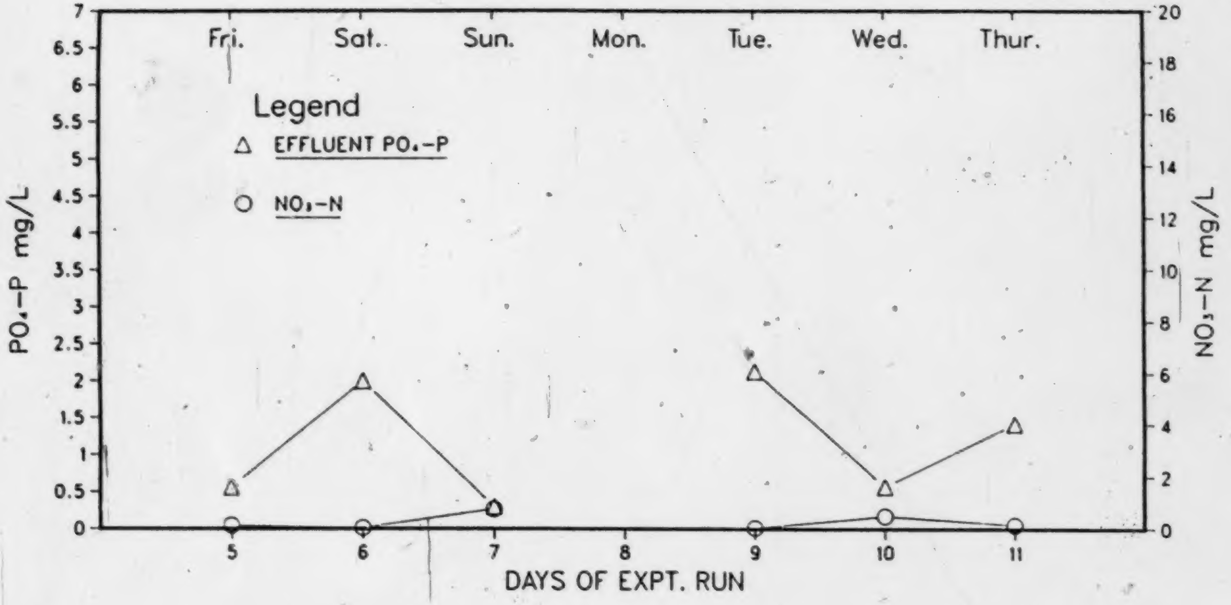


Figure III.61 Effluent $PO_4$-P and Effluent $NO_3$-N For Reactor Number Five Throughout the Sampling Period.

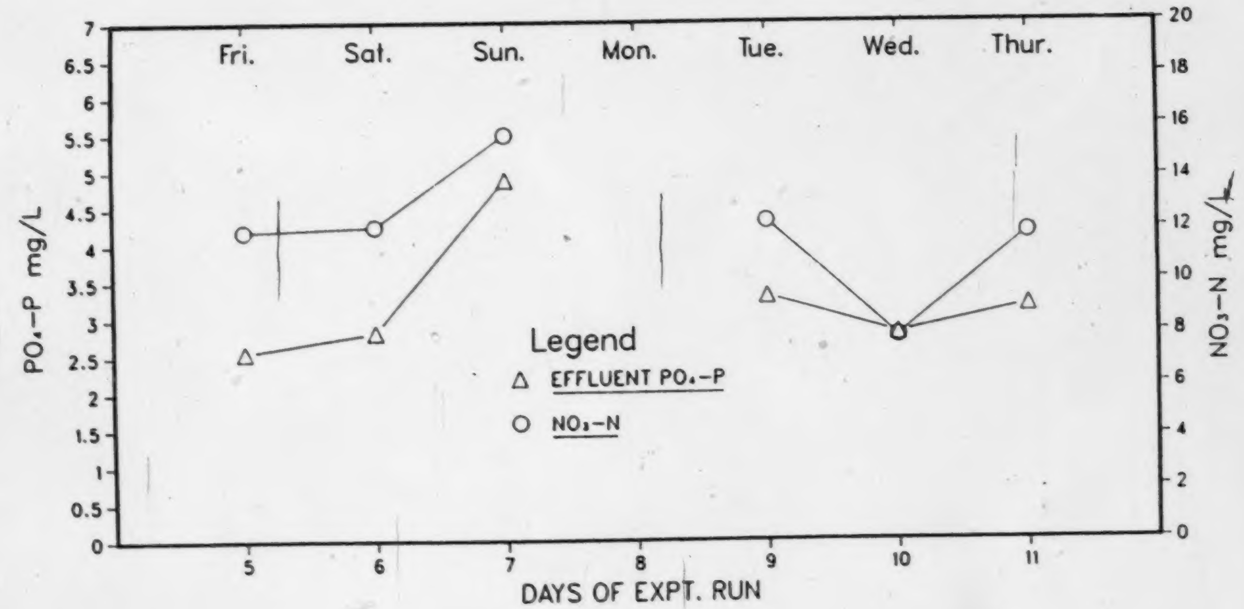


Figure III.62 Effluent $PO_4$-P and Effluent $NO_3$-N For Reactor Number Six Throughout the Sampling Period.

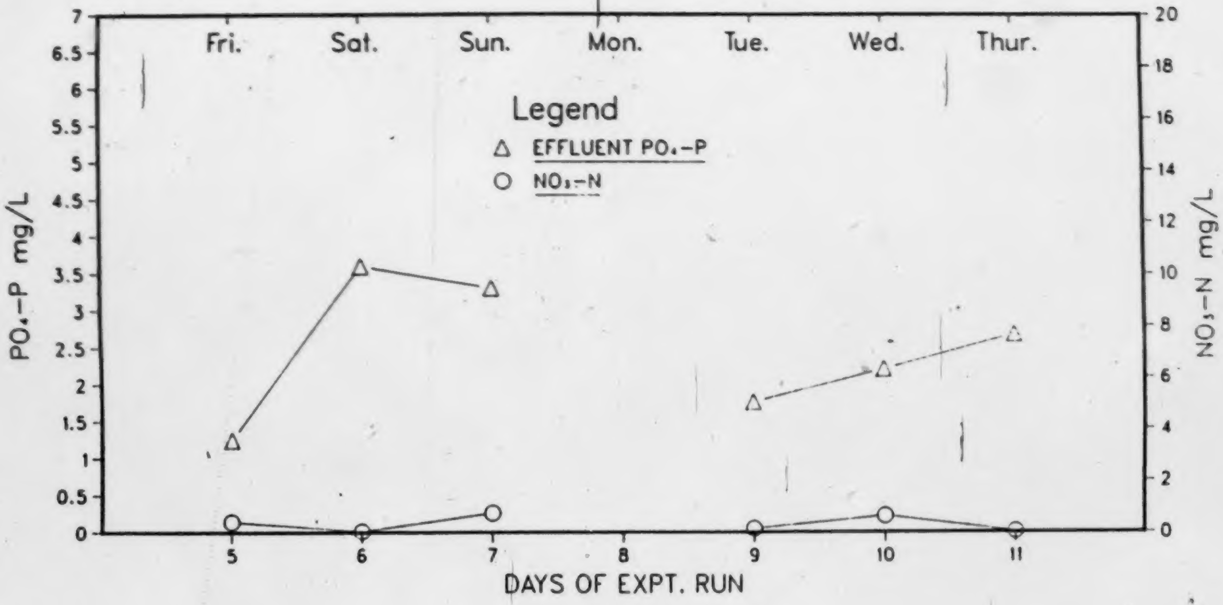


Figure III.63 Effluent $PO_4$-P and Effluent $NO_3$-N For Reactor Number Seven Throughout the Sampling Period.

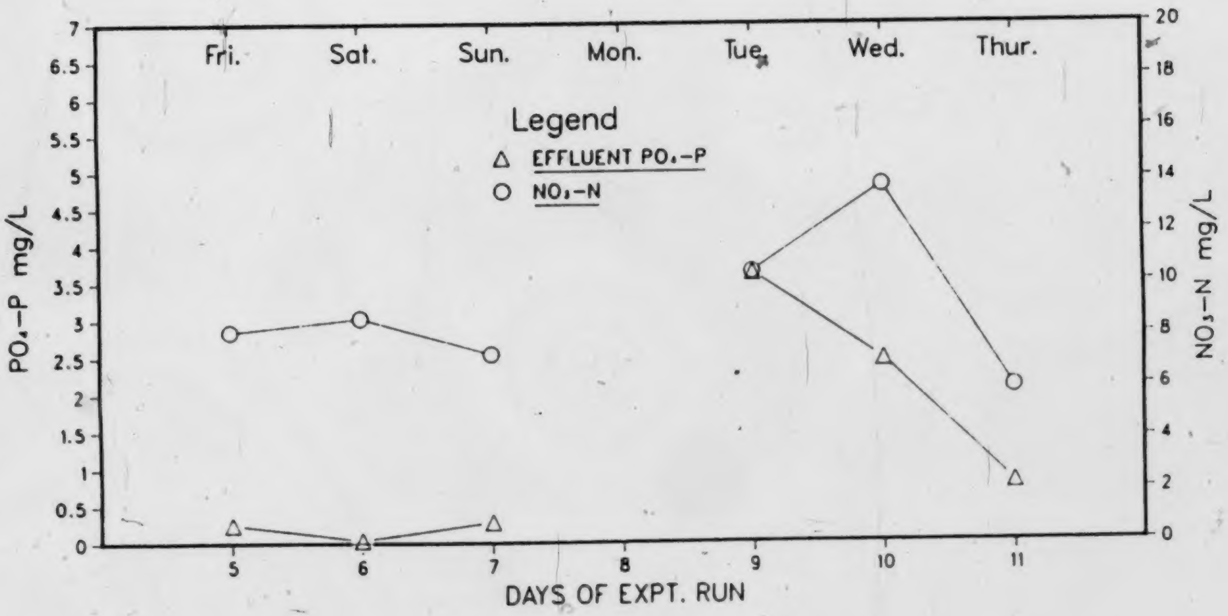


Figure III.64 Effluent $PO_4$-P and Effluent $NO_3$-N For Reactor Number Eight Throughout the Sampling Period.

## APPENDIX IV

### EXAMPLE OF FACTORIAL ANALYSIS

As an example to demonstrate the factorial design technique the phosphorus removal results of day 5 can be considered. The variables investigated were:

7. Aerobic nominal detention time;
8. Anaerobic nominal detention time;
9. Sludge age (or MCRT).

In order to quantify the effects of these variables on the overall removal it was decided to vary them over high and low levels. The high and low levels chosen were as shown in Table IV.1.

The results of the eight ($2^3$) runs, or trials, obtained for day 5 are shown in Table IV.2.

Table IV.1 Levels of Variables in Phosphorus Removal Factorial Experiment

| | Low Level | High Level |
|---|---|---|
| Aerobic nominal detention time, hours | 1.68 | 5.04 |
| Anaerobic nominal detention time, hours | 0.84 | 3.36 |
| Sludge Age, days | 5 | 15 |

Table IV.2 Results of Phosphorus Removal Experiment on Day 5

| Run Number | Aerobic Time | Anaerobic Time | Sludge Age | Effluent Phosphorus |
|---|---|---|---|---|
| 1 | 1.68 | 0.84 | 5 | 1.29 |
| 2 | 5.04 | 0.84 | 5 | 2.25 |
| 3 | 1.68 | 3.36 | 5 | 2.98 |
| 4 | 5.04 | 3.36 | 5 | 0.75 |
| 5 | 1.68 | 0.84 | 15 | 0.56 |
| 6 | 5.04 | 0.84 | 15 | 2.55 |
| 7 | 1.68 | 3.36 | 15 | 1.25 |
| 8 | 5.04 | 3.36 | 15 | 0.25 |

From Table IV.2 it can be seen that the only difference in the variable setting between run number 1 and run number 2 is the aerobic detention time used. It is therefore assumed that the difference in removal between the two runs is due to the changed setting of aerobic detention time. Therefore it appears that increasing the nominal aerobic detention time from two to six hours caused an increase in effluent phosphorus from 1.29 mg/L to 2.25 mg/L, i.e. a change of 0.96 mg/L.

A similar situation exists between runs 3 and 4, runs 5 and 6 and runs 7 and 8. The changes in removal were -2.33 mg/L, 1.99 mg/L and -1.00 mg/L, respectively. The minus signs indicate an increase in phosphorus removal. Thus the average effect of changing the nominal aerobic detention time from 2 hours to 6 hours can be calculated. This quantity is termed the main effect of the aerobic detention time.

Main effect of aerobic detention time

$$= 1/4(0.96-2.23+1.99-1.00) = -0.07 \text{ mg/L} \qquad [IV.1]$$

On average, increasing the nominal aerobic detention time from 2 hours to 6 hours produces a decrease in effluent phosphorus of 0.07 mg/L. It is unlikely that a number of such small relative magnitude is a significant result of factor settings, however it has been retained here for purposes of illustration of the factorial design method.

Considering runs 1 and3, 2 and 4, 5 and 7 and 6 and 8 the main effect of anaerobic detention time is calculated as -0.36 mg/L. The main effect of sludge age is calculated as -0.67 mg/L from runs 1 and 5, 2 and 6, 3 and 7, and 4 and 8.

Investigation of the calculation of the aerobic detention time main effect shows that the same change in aerobic detention time did not always produce the same change in effluent phosphorus concentration. The variation was greater than was expected to result from experimental measuring variations alone. The only other changes in the system were the settings of the anaerobic detention time and the sludge age. The variables are said to have interacted and it is necessary to quantify this interaction.

Consider the influence changing the anaerobic detention time has on the effect of increasing the aerobic detention time. Firstly, the effect of changing the aerobic detention time while the anaerobic detention time is at its low setting can be found. Two estimates of this are available and are represented by the differences in results for runs 1 and 2, and runs 5 and 6. These differences are respectively, 0.96 mg/L and 1.99 mg/L. Thus the average effect of aerobic detention time at a low anaerobic detention time is 1.48 mg/L.

Next a similar calculation using runs 3 and 4 and runs 7 and 8 gives the average effect of aerobic detention time at a high anaerobic detention time as -1.62 mg/L. It can be seen that a difference of -3.1 mg/L exists in aerobic detention time effect as a result of increasing anaerobic detention time. Half this number (i.e. -1.55 mg/L) is by convention termed the aerobic detention time x anaerobic detention time interaction.

Other interactions can similarly be calculated. These are termed two level interactions. It can easily be shown that the two level interaction is the same in either direction, i.e. the aerobic detention time x anaerobic detention time interaction has the same value as the anaerobic detention time x aerobic detention time interaction. In fact this is true of all two level interactions.

A three level interaction will also exist but it is generally small. In this case the aerobic detention time x anaerobic detention time interaction may be influenced by the setting of the third variable, sludge age. This is the aerobic detention time x anaerobic detention time x sludge age interaction. It may be calculated as follows. The three level interaction is defined as half the difference between any two level interaction at the high level of the third variable and the same two level interaction at the low level of the third variable.

In the present case at a sludge age of 15 days the aerobic detention time x anaerobic detention time is calculated.

Aerobic detention time x Anaerobic detention time interaction

= ½[(0.25 - 1.25) - (2.55 - 0.56)] = -1.50 mg/L [IV.2]

At a sludge age of 5 days the interaction is similarly calculated.

Aerobic detention time x Anaerobic detention time interaction

= ½[(0.75 - 2.98) - (2.25 - 1.29)] = -1.60 mg/L [IV.3]

The three level interaction is then calculated. Aerobic detention time x anaerobic detention time x sludge age interaction

= ½[-1.50 - (-1.60)] = 0.05 mg/L [IV.4]

This number is small and may be due only to random measuring variation indicating that any two level interaction is independant of the third variable. It is the measurement of interactions which makes the factorial design an extremely useful experimental tool.

The calculated values for the effects and interactions are shown in Table IV.3 in which 1 represents aerobic detention time, 2 represents anaerobic detention time and 3 represents sludge age. The interactions are labelled as combinations of these.

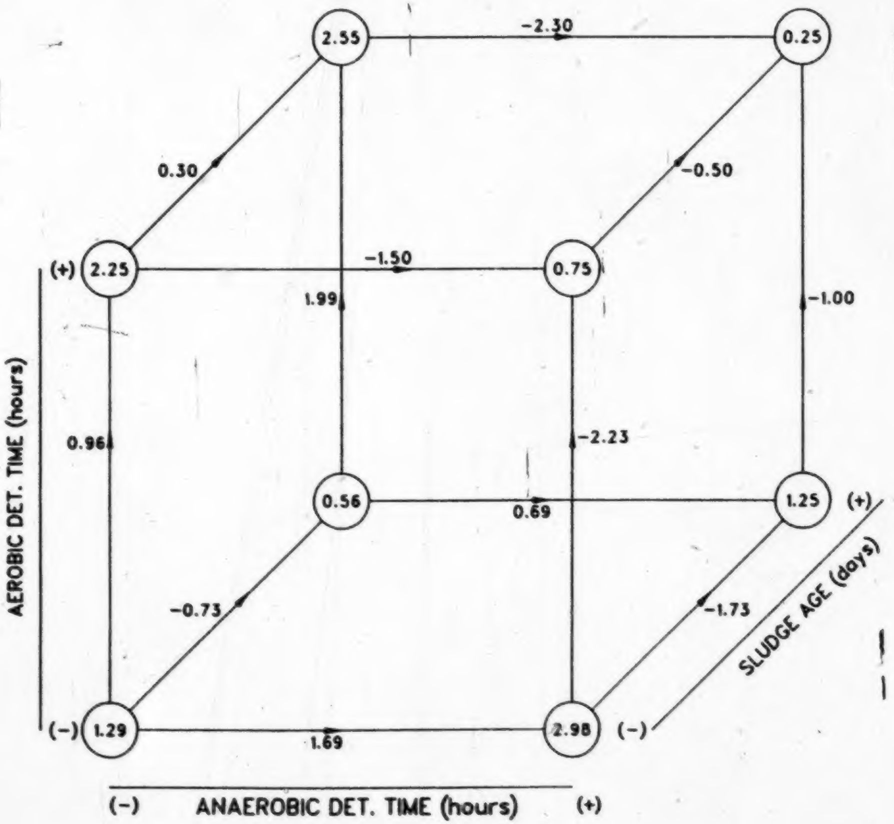
# Table IV.3 Effects and Interactions from Phosphorus Removal Factorial Experiment (Day 5)

| Main Effects | mgP/L |
|---|---|
| 1 | -0.07 |
| 2 | -0.36 |
| 3 | -0.67 |
| **Interactions** | |
| 12 | -1.55 |
| 13 | 0.57 |
| 23 | -0.45 |
| 123 | 0.05 |

The interpretation of these results is similar to that shown in Section 6.3. Since the numbers calculated may in part be due to random fluctuation and measurement variation as well as to the variable settings, techniques are applied to the results to factor out these contributions. The Analysis of Variance technique of Fisher in particular is used and has also been described in Section 6.

As an aid to visualizing the $2^3$ factorial design it is often presented as a cubic experimental space in which the eight runs are positioned at the eight vertices of the cube. This is shown in Figure IV.1.

The above discussion of the factorial design is neither exhaustive or complete. For further in-depth analysis of the procedure and concept the reader is referred to the textbooks mentioned in Chapter 3.



2.55
-2.30
0.25
0.30
-0.50
(+)
2.25
-1.50
0.75
1.99
-1.00
AEROBIC DET. TIME (hours)
0.96
-2.23
0.56
0.69
1.25
(+)
-0.73
-1.73
SLUDGE AGE (days)
(-)
1.29
1.69
2.98
(-)
(-)
ANAEROBIC DET. TIME (hours)
(+)

Figure IV.1 Cubic Representation of $2^3$ Factorial Design Experimental Space (Day 5 data used as an example).